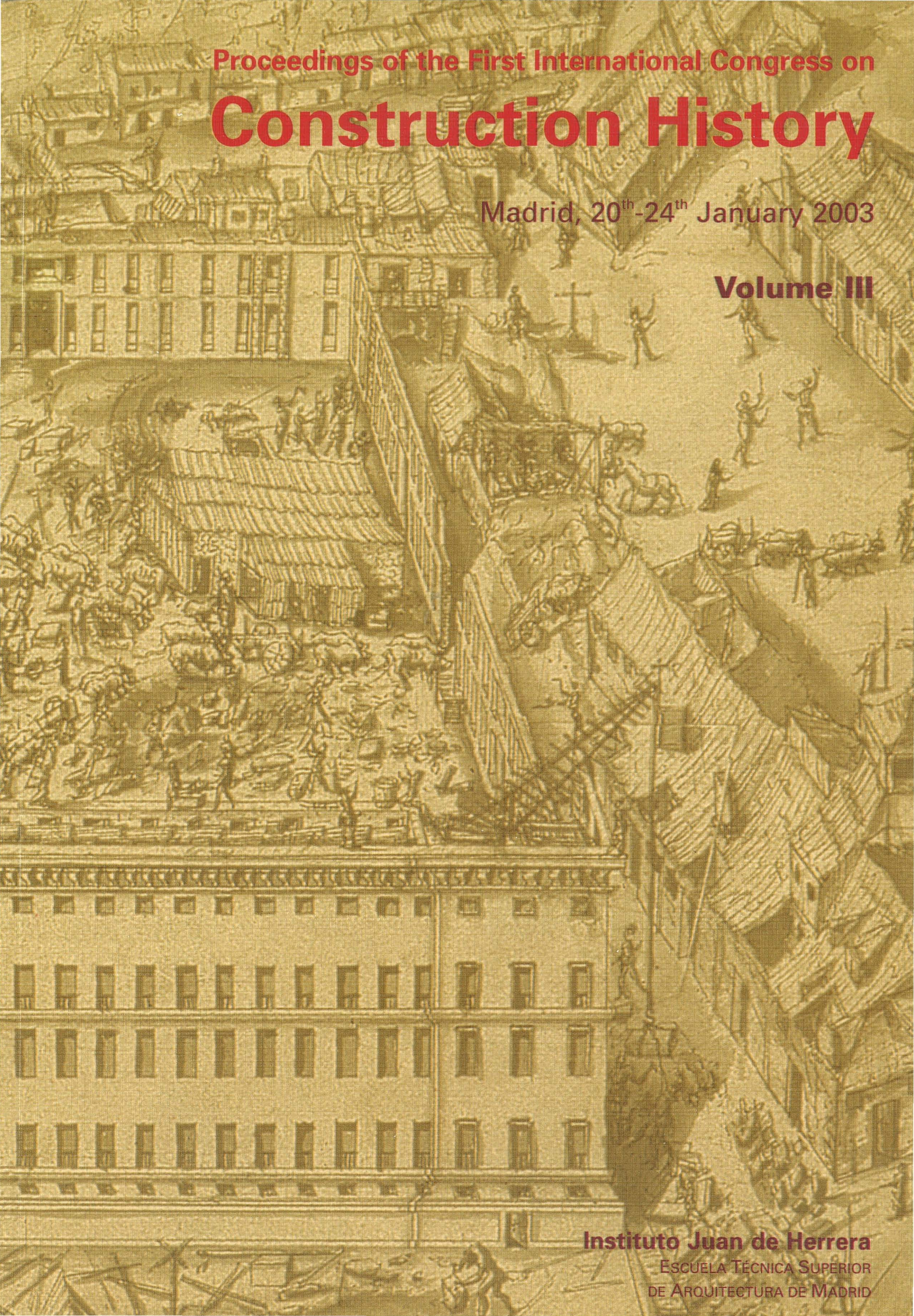

Proceedings of the First International Congress on

Construction History

Madrid, 20th-24th January 2003

Volume III

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Contents

Iron constructions for factory buildings in Berlin in the nineteenth and early twentieth century

Miron Mislin

Paradoxically iron constructions which were decisive for the development of Berliner metal and metal tool industries were seldomly and only gradually applied from 1837 through 1870 for the erection of shops and factories, at that often in combination with wooden elements of construction. (The oldest industrial building of Germany, the foundry assembly hall built by C. G. Langhans (1825), is not in Berlin). The first cast and wrought iron weight carrying structure for utilitarian buildings in Berlin was constructed for the storehouse of the Schickler'sche Zuckersiederei (1835) by F. Hesse, after having visited England, and the first inner iron skeleton construction was erected by L. Persius and L. Dannenberger on the Mühlendammbridge (1844–48).

Essential for the use of iron constructions was the challenge of fire protection. The conflagrations of 1831 and 1838 which destroyed the Factory of Cockerill and the Dammmühlen, and the fire which ravaged the opera (1843) gradually set off more and more the use of the new building material iron in the Berliner construction engineering. As early as 1831 fireproof iron roofings were built for steam boiler shops. All the same iron constructions had been built abroad much before that, for instance structural systems for mills and storehouses in England. Also market halls were erected with iron elements. But for economical reasons the building material iron was only used for Berliner shops and factories by the 40's.

The late works of the architect K. F. Schinkel, such as the Bauakademie (1831–35) and the Packhofspeicher (1835) served partly as model for the emerging Berliner industrial architecture. Both buildings have been cited in the literature of the history of architecture as landmarks of construction. They were looked upon as anticipation of serial building as well as forerunners of modern skeleton and frame constructions (Ausstellungskatalog 1981). K. F. Schinkel had experienced impulses from English factories which he had investigated during his study trip to England 1826 (Riemann 1986). The English stripped down, utilitarian architecture of warehouses and docks were though not taken into account by Schinkels followers, although a new critical point of architecture and construction had been achieved with the Albert-Docks in Liverpool (1841–50). The early English iron constructions influenced the construction of industrial architecture and railway station buildings in Berlin though also by first hand information (Frühauf 1991).

In the following a selection of iron construction elements, columns, roof constructions and floor structural systems are going to be displayed, to illustrate the specific development in Berlin.

Columns

The slender iron cast columns gradually got carried out in Berlin since the 40's, partly because the unbreakable wooden counterparts in warehouses and factories needed a diameter of 0,50 cm. Normally the

large supporting capitals carried two beams as joist (for instance: industrial courts at Bethanien-Damm 59, Leuschner Damm 9, Waldemarstraße 27). The architect L. Hesse proposed for the above cited fireproof storehouse building also cast iron hollow columns for all the four stories, following English models. The beams and joists were performed though in wood. The stories rested on three rows of columns with a diameter of 18, 3 cm, 15,7 cm and 13 cm, the wall thickness being 1,3 cm. Die lower columns had to carry a compressive stress of approx. 1 600 kg, having a weight of approx. 260 kg each. (fig. 1).

Chronologically the columns of Hesses' storehouse building were followed up by shops and factories for A. Borsig (1837–40, 1844 and 1861) in Berlin, however only for groundfloor assembly halls. The master carpenter G. Scharnweber designed cast iron columns for the saw tooth roof hall of the carpet weaving mill Preatorius & Protzen at the Engelufer (1854). These columns had at the height of the transmission roller flat fixed cast plates which served as basis for the brackets. (fig. 2) Likeweise the smithy shop of F. A. Egells at the Chausseestraße 2 was erected with hollow cast iron columns (1851), following experiments in the assembly shop where iron supports with a height of over 5,76 m had been built and the construction of a two storied administration building was breadthwise bridged over by a row of columns.

In the years 1844–48 the Royal Mills at the Mühlendamm were erected with an inner iron skeleton construction. Hollow columns with a diametre of approx. 36,5 cm up to 20 cm were used from the ground to the floor carrying in the transverse and longitudinal direction fish belly shaped railway metals above the capitals (Rothe 1849).

Leaving aside the cast iron columns of the saw tooth roof hall of W. Borchert at the Kochstraße 30

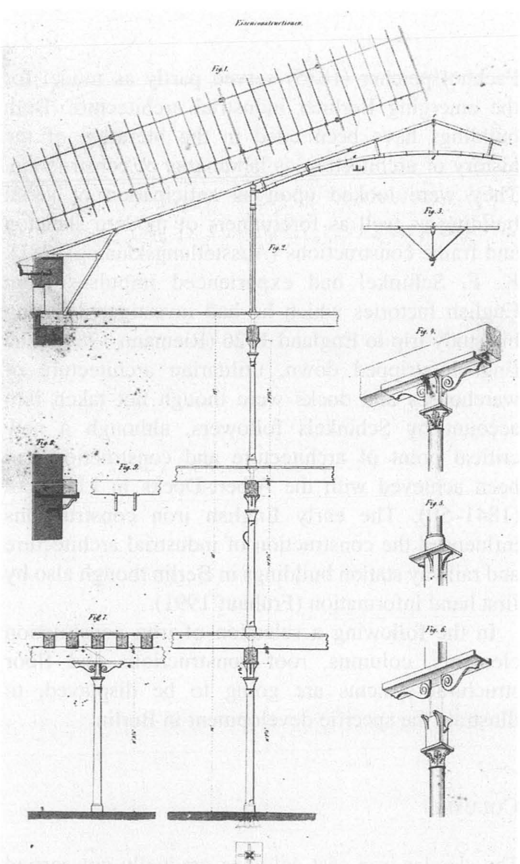


Figure 1
Storehouse for the Schickler'sche Zuckersiederei, 1835, details of the construction

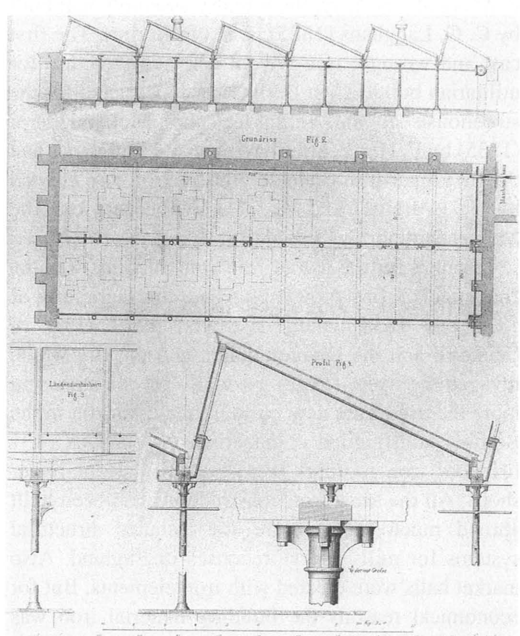


Figure 2
Carpet weaving mill, 1857, saw tooth roof

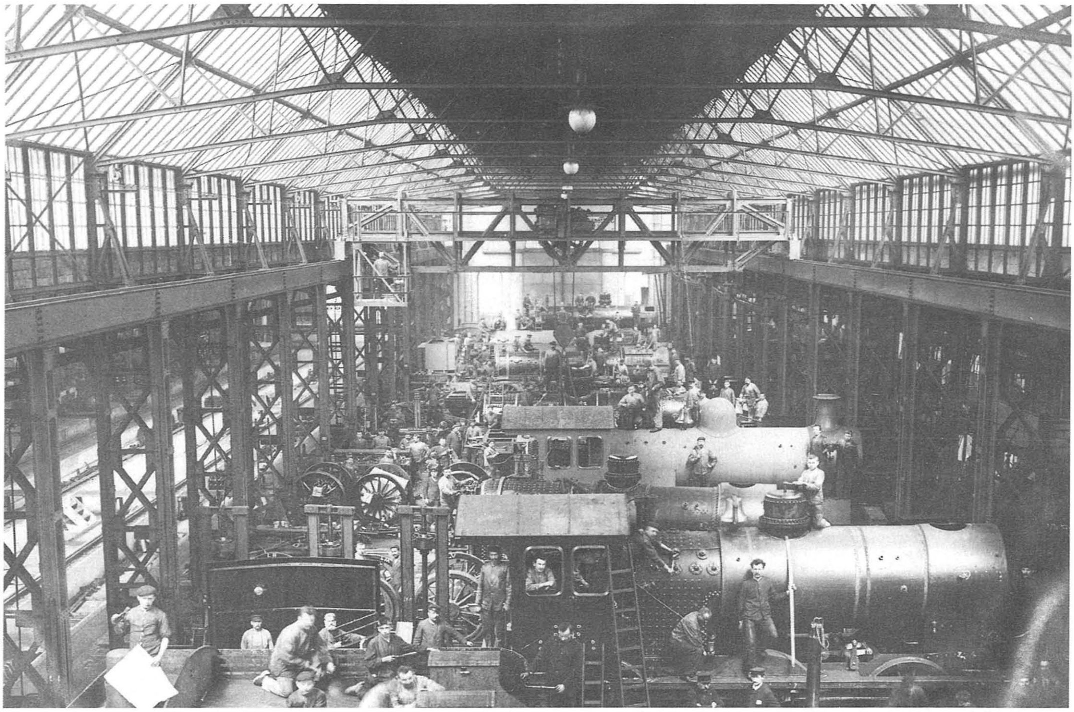


Figure 3
Locomotive assembly hall A. Borsig, 1844, latticed columns

built in 1866, the most outstandig constructions with iron columns before 1880 that should be mentioned were the low buildings of the Royal Artillerie shops at Spandau and the railway shops of the Royal Eastern Railway.

Also the famous factories of L. Loewe at the Hollmannstraße 32 (1870–1882), just like the grinding department and the assembly hall at the Huttenstraße 17–20 (1896–98), were erected with iron columns. In the same way the seven stories of the Ermeler-Tobacco factory at the Breitenstraße 11 (1877–78) rested on rows of cast iron columns with a diametre of 15 cm up to 42 cm.

Cast iron columns were used for shops and assembly halls up to the 90's, for instance at the Kappler'sche factory for mill building at the Prinzenallee 75–76 (1890), at the industrial court at the Adalbertstraße 70 (1898), at the dyeworks Schwendy at the Köpenicker Straße 7a (1894), and even at the mounting shops Schäfer & Walcker at the Lindenstraße 18–19.

Riveted and screwed wrought iron columns were in use in Berlin for industrial architecture only after 1890. The supports were assembled to I, L, and E profiles which were held together by cross-shaped or diagonal flat irons. In this manner the assembly shops of C. Flohr, at the Chausseestraße 28, and of L. Schwartzkopff at the Chausseestraße 20, both machine shops of L. Loewe (1895 and 1897) at the Huttenstraße 17, and at the Wiebestraße which were torn down in 1994, showed these latticed columns. Also the foundry of A. Borsig at Berlin-Tegel (1896–97), just like the boiler plant at the same place (1896–98), and the locomotive hall (1900) were erected with latticed columns. (fig. 3) The AEG machine factory at the Feldstraße- and Ackerstraße (1896–98), the AEG turbine hall at the Berlichingenstraße (1908), and the AEG machine shops at the Brunnenstraße 107a were furnished with steel columns, often with a rectangular cross section. (fig. 4).

In the early phase of industrialization (1808–40) it was possible to find out the reaction, the bending

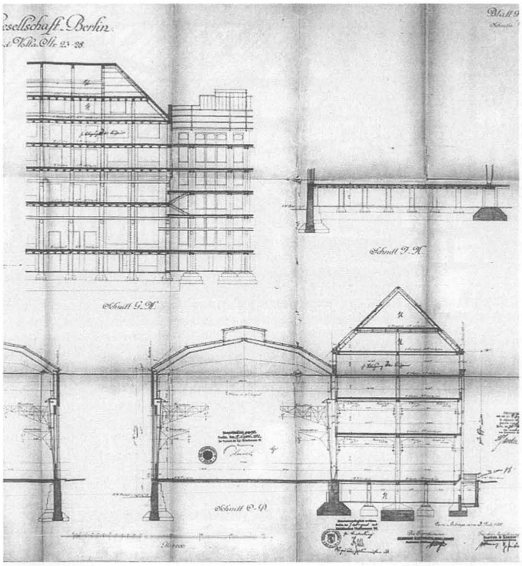


Figure 4
AEG Voltastraße 8–29, 1911, steel columns

moment as well as lateral loading and shearing forces of weight-carrying structures analytically and partly relying on the parallelogram of forces. The tabular data for strength tests of different materials and their best cross section allowed every academically or practically trained master builder or master craftsman to define the dimensions for roof structures and floor constructions, iron columns and masonry walls.

In the 60's it was possible to determine the cross section of iron girders by calculating the second moment and the section moment. Stress transfer of the beam support and frame work truss which was often used for industrial buildings could be estimated by the Ritter'sche method and following the rules of «graphical statics» by C. Culmann.

For the first time static stability had to be proven according to public announcement from August, 2nd 1864. Paragraph 14 of the announcement asked for «all iron cast construction elements to be in such dimensions as to garantee under continuous stress an absolute stability of 2,5 kg/per 2 mm2 and a relative stability of 5 kg/per 2 mm 2, and for wrought iron a stability of 7 kg/per 2 mm 2». The static calculations and the garantee for iron constructions were furnished by the contracting firms for iron constructions.

Roof structures

According to commentaries of L. Klasens the architect L. Hesse also designed the first saddleback roof with the building material of wrought iron in Prussia for the already above mentioned storehouse (Klasen 1876). The construction of the roof resembled a wooden construction with double-posts-roof, however did not take into calculation loads due to wind and snow. The placing of the bowstring girder, rafters and struts to eleminate the arch trust followed the French wrought iron constructions, foremost the market hall of Magdalena in Paris (Allgemeine Bauzeitung 1838).

The roof construction of the machine shop of A. Borsig at the Chausseestraße (1844) also followed the model of the triple roof of the Magdalena market hall. For the span of 16,75 m a triangular system with rafters and beams measuring 22,5 cm × 15 cm was chosen. The iron elements were cast iron rafter heads and supporting purlins, wrought iron diagonal members and round tension rods which were secured by eye bolts.

The of recent rediscovered drawings disclose that A. Borsig did not carry out plain iron constructions at his first machine shops at the Chausseestraße (1837–44). Borsig's craft masters A. Pardow and A. Karchow built 1844 a noticable framework construction of an English three-dimensional purlin with lifted horizontal tiebacks, following the models of roof system of the machine shop of the London-Birmingham-Railway (1836) and the Hungerford market hall in Manchester (Allgemeine Bauzeitung 1838).

In 1844 the roof of the Borsig locomotive hall at the Thorstraße was erected with a slightly improved English triangular rafter system without purlins. To cope with the span of 18,78 m the English models of triangular roof systems which were introduced for the railway station halls and passangers waiting rooms of the London-Birmingham-Railroad (1836) were followed. The roof framing was put together by two flat iron guide rails (7,62 cm × 1,27 cm), rafters filled with wooden battens, cast iron struts with T-shaped cross sections, vertical suspension rods as well as tiebacks which coped with the shear strength of the rafters (Mislin 2002). (fig. 5).

This construction system was not only used for market halls and railway stations in England. In the

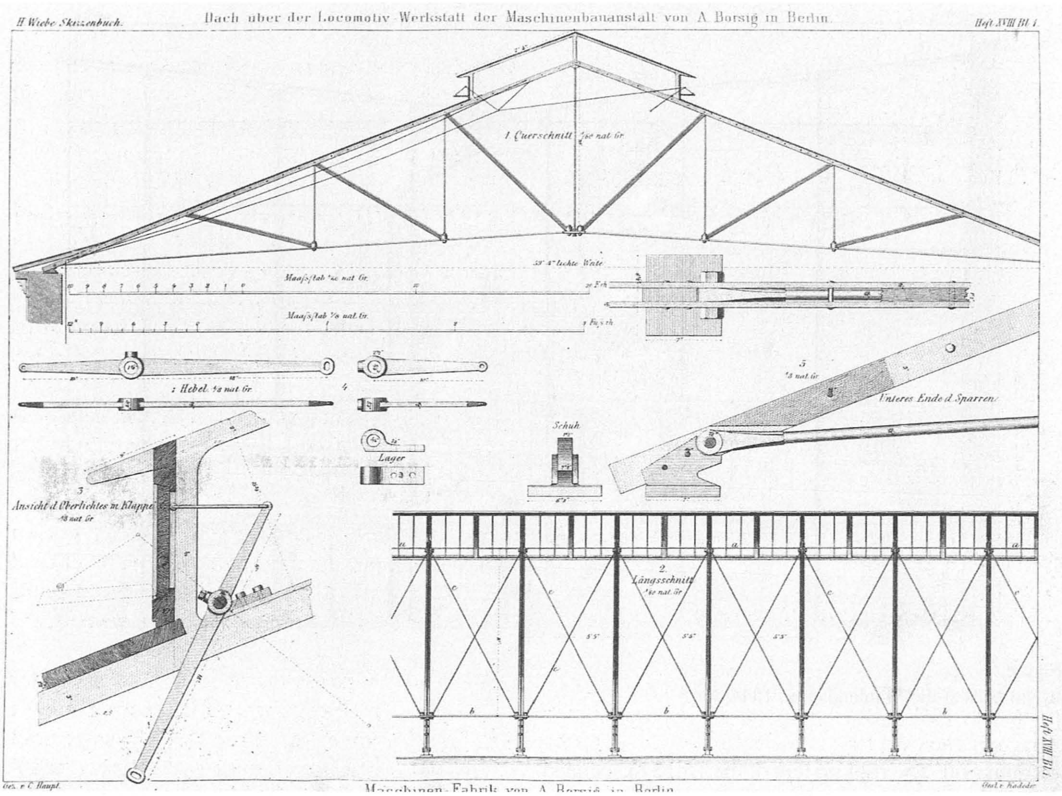


Figure 5
Locomotive assembly hall A. Borsig, 1856, addition

50's the roof of a foundry of the Austrian Lloyd in Trieste was built in a similar way as the Borsig's roof with a rafter system. Through to the 70's this English triangular rafter system was mentioned in the manuals for building constructions of E. Brandt and L. Klasen (Allgemeine Bauzeitung 1857; Brandt 1871).

The Borsig machine shops at the Chausseestraße being mainly roofed with wooden carpenter roof structures and only very rarely with combined hanging trusses made of iron and wood, the resurrected Royal mills at the Mühlendamm displayed with the skeleton construction a total innovation which remained unrivaled for a long time. The unsual roof structure was sloping from both sides to the middle of the building. The rafters of the pent roof and the joints were T-shaped rails, whereas the beams were constructed with cross-shaped cast iron profiles. The drawings for the Royal Mills belonged to the property of the Prussian Fiscal Department, being drawn up by the Hofbaurat L. Persius and the mill builder Dannenberg (Wiebe 1861). (fig. 6).

The latticed girder which was put to use in the late 40's in bridge art, was introduced to rising structures with great delay. The roof structure of the market hall at the Rue du Chateau d' Eau (1857–58) was designed prior to a construction of the saw tooth roof for the Artillerie shops at Berlin-Spandau for which the rural masterbuilder Beyer had succeeded in calculating for a latticed girder in transverse direction (1868) (Wiebe 1859). (fig. 7).

A. Borsig executed a number of interesting roof constructions for his shops in the years 1848–58 which were inspired by the bridge constructions in

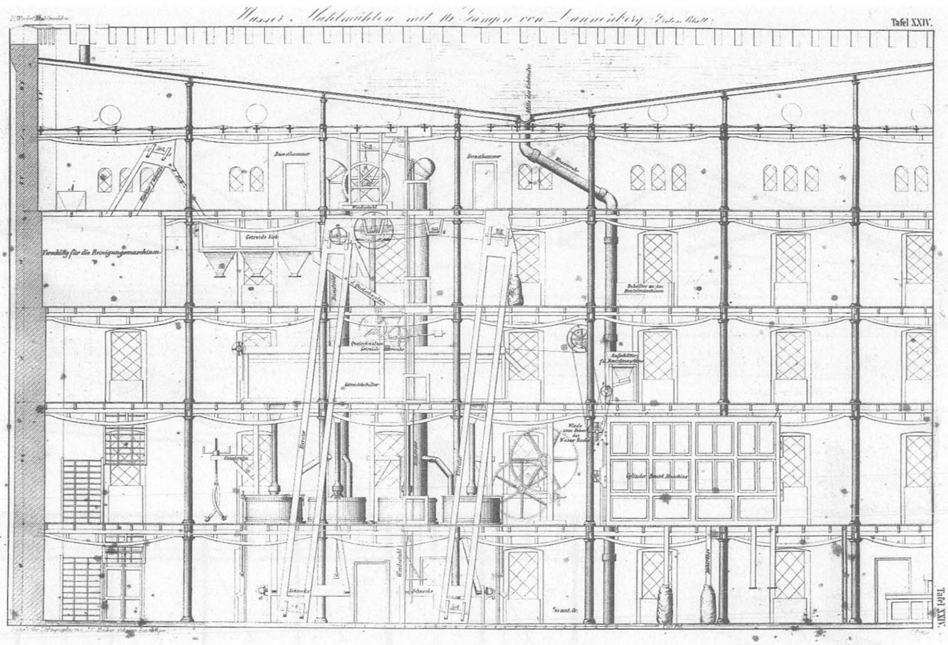


Figure 6
Royal Mils at the Mühlendamm, 1844-48

commission. The roof system of the 15,12 m spanned joinery was built by the masonry and carpenter masters A. Pardow and H. Müller built as rafter roof construction with suspended double pitch-roof and tiebacks, suspended and diagonal rods of round bar-steel. Nearly at the same time with the erection of the railway station Hamburger Bahnhof (1847–49) A. Borsig built his new rolling mill in Berlin-Moabit. The roof system of the rolling mill was put together by latticed girders with tiebacks which spanned over a width of 15,20 m and 21,50 m. Because of the great arch trust the butments were supported by the massiv external masonry wall which was ornamented by the architect J. H. Strack like a fortress so that the roof construction was hidden. This constructural inconsistency was overcome by the latticed girder roof system of the hammer mill hall (1852–54) with a complete barrel vault roof which most probably is unique in the history of industrial building architecture, performed as one-room construction without intermediate columns and spanning a total of 21,20 m (Mislin 1993).

In this context special mention should be made of the barrel vault roof designed by the A. Borsig shops

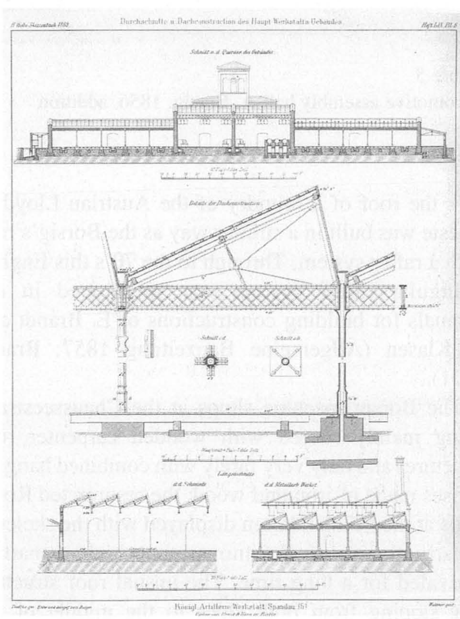


Figure 7
Artillerie shop Spandau, 1857–58

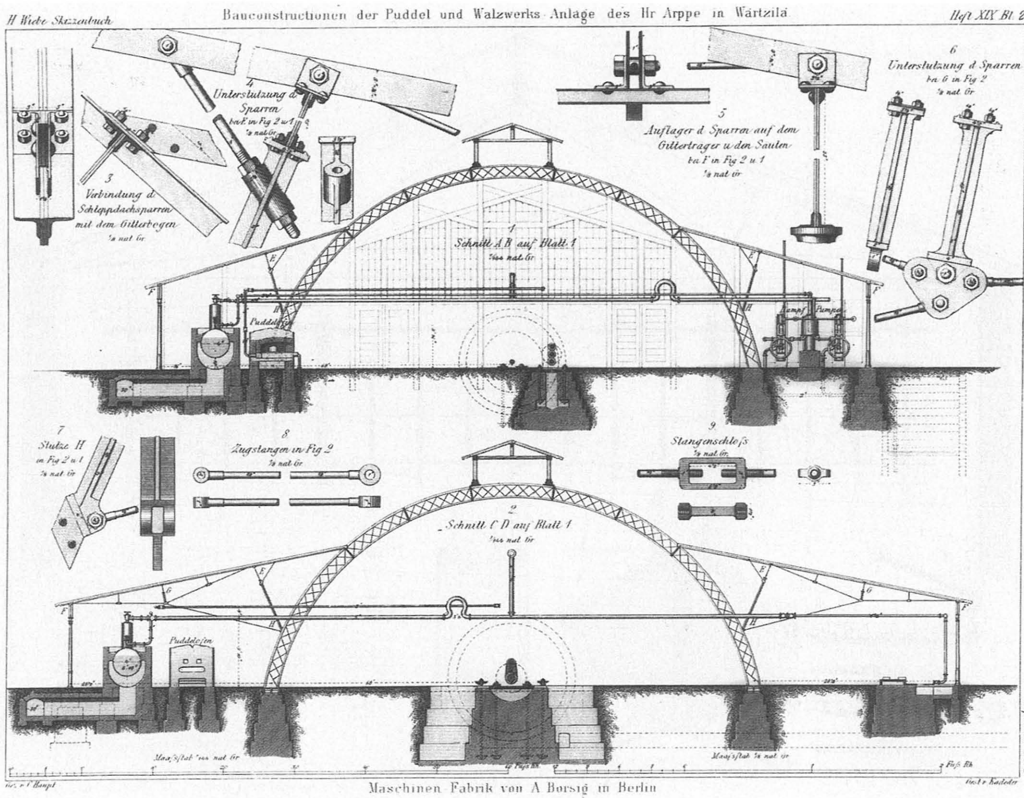


Figure 8
Barrel vault roof A. Borsig, 1852–54, one-room building

for the Dortmunder Bergbau- und Hüttengesellschaft and for the muck and rolling mill in Wärtzlila/Finnland (1853–56). Amazingly the firmly fixed framework latticed girder with walled in tiebacks beneath the floor and spans for the roof frame of 2,10 m, 23,25 m and 24,80 m, and lantern towers were built before W. Barlow succeeded in erecting the St. Pancras station in London (Wiebe 1859). (fig. 8).

!856–57 the master craftsmen A. Pardow and O. Sauerteig built a Polonceau truss covering the tender shop of A. Borsig at the Thorstraße 48–53, composed of a series of united triangles (Mislin 2002). The iron vertical elements called for a static calculation of the roof structure which was carried out by the master craftsmen. Remarkable for the history of constructions is the fact that up to this date the statistic calculating engineer J. Weisbach had not calculated Polonceau trusses in the second edition of his manual «Statics of solid bodies» (1850–51). (fig. 9).

However the first Polonceau truss of the Berliner industrial buildings most probably was built 1851 for the smithy of F. A. Egells at the Chausseestraße 3, spanning 12,60 m. 1856–58 also the machine shop of A. Borsig at the Chausseestraße 1 made use of three Polonceau trusses with spans of 11,83 m, 18,37 and 10,50 m, the construction combining wood, cast and wrought iron.

Whereas the struts of the Polonceau trusses remained through the 90's fabricated of wood with a rectangular cross section of 21 cm × 21 cm, the compression columns were usually made of cast iron rails and the tie rods of round rod-steel. For the ironworks A. Borsig at Berlin-Moabit the first Polonceau truss, made of flat and angle iron was carried out (LAB Rep 226).

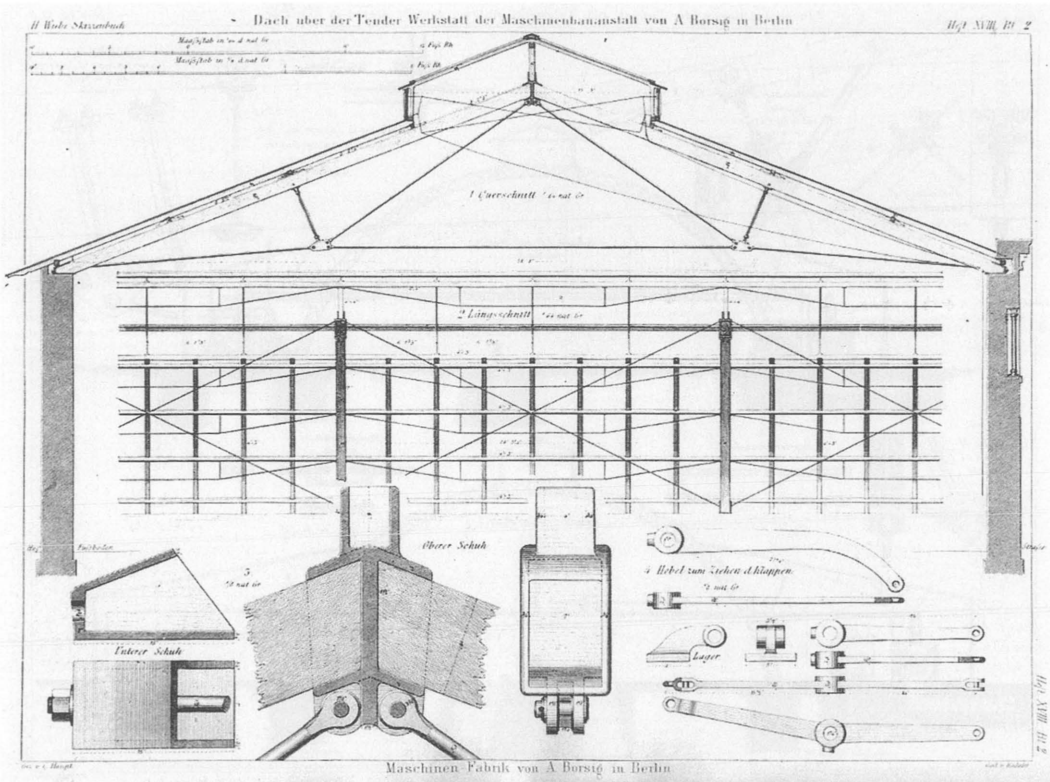


Figure 9
Polonceau truss roof A. Borsig, 1844, 1856

1866 the building master Bayer developed for the Artillerie shop at Spandau a saw tooth roof truss with beam support. Equally new was the triangular frame work with lantern which was executed for the hammer smithy of Schwartzkopff at the Ackerstraße 96 made of wood and iron rod diagonals, covering a span of 23,50 m. (fig. 7).

Beginning at the early 70's more and more iron constructions were put to use for all kinds of roof framings. The cast iron roofs did not display transverse distribution which had been normally employed for the wooden systems shallow pitch roofs by using roof joists. All the more it became of importance to make use of tension elements in oder to balance the rafter shear. By manufacturing triangulated systems the roof structures were ment to be non-sliding supporting structures.

Already in 1882 A. Vogt designed a machine shop for the L. Loewe Kreuzberg complex with an innovative iron construction. The garden court at the Alte Jacobstraße had already been built over by the machine shop, and the remaining side wings were left without free spaces. In closing up to these buildings with a western annex new constructive ideas were performed, such as roof and axial construction made of rolled bars, wrought and cast iron supporting elements and cast iron columns. The placing of the assembly hall between the already existing wings without windows resulted in a completely glazed roof pane. A grid of steel angles held panes of glasses measuring 75 cm × 75 cm. This roof-lighting system could compete with the later on erected halls at Moabit (1896–98), and the assembly halls of AEG, A. Borsig and Siemens & Halske, built in the years 1896–99 and 1908–10. (fig. 10).

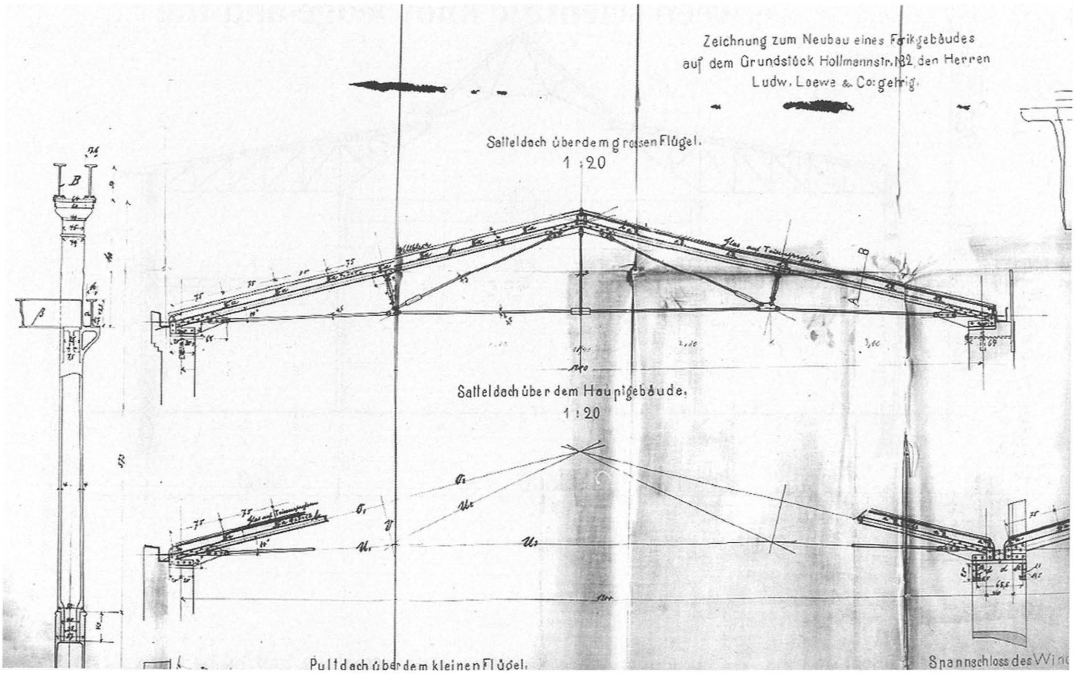


Figure 10
Machine hall L. Loewe, 1882

Already in the 80's frame work trusses, at times also parabolic girders or solid wall girders, were used for assembly halls; 1884 and 1888 the master craftsman P. Buchow built for the paint manufacturer Beringer a triangulated steel framed structure with T- and L-shaped iron diagonals, the short vertical members being in compression, the longer ones in tension, and a span of 16 m. Also the 16 m and 24 m wide spanned truss girders for the machine shop L. Schwartzkopf designed by C. Scharowsky were made of rolled iron section (1891), the first truss being a very unusual lantern and allowing for aeration. (fig. 11).

Similar lanterns were inserted into the roof pane of the framework built for the AEG machine shop, at the Brunnenstraße 107a, by the master builder P. Tropp. In the same year Siemens & Halske had built an assembly hall on their land at Salzufer/Franklinstraße 27–29 with a saw tooth roof, the roof floor and the gallery floor being furnished with rolled iron section. For the machine hall of L. Loewe at the Wiebe-/Huttenstraße A. Vogt designed 1897 a bented steel framework with polygonal top boom (resp. 9,70 m and 10 m). (fig. 12) This fourfold-bented-buttress framework with vertical strutts and steep rafter pitches under the skylights near the wall was in design and construction a real novelty of the Berliner hall buildings which was only topped by the frame system of the AEG assembly hall at the Hussitenstraße (1911) (Mislin 2002). (fig. 13).

In 1896–98 the roofing work of the boiler-smithy and the foundry of A. Borsig at Tegel was carried out with a double-bented-buttress-truss, a kind of threefold Polonceau truss —spanning 18 m up to 19 m. Tall trussed girders with altered threefold Polonceau trusses were also used for 16 m wide halls in America (for instance Boyer Machine Co./Detroit). (fig. 14).

The state of the art for roof constructions before 1900 is demonstrated by the framework with upper flange and tieback at the foundry of A. Borsig at Berlin-Tegel, and by the triangular framework with rising diagonals for the machine shop of L. Sentker at the Müllerstraße 10 (1899) (span 20 m). The beginning of the century is characterized by the three-hinged-framed truss for the AEG turbine hall at Moabit

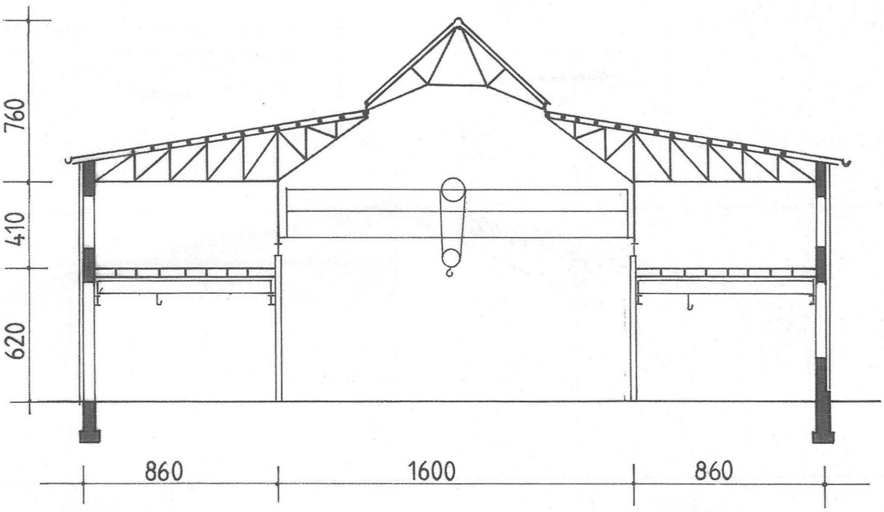


Figure 11
Assembly hall L. Schwartzkopff, 1891

(1908) (span 25,10 m), and the AEG machine hall at the Hussitenstraße (1911). (span 31 m) (fig. 15).

Compared with the turbine hall the novelty was the consistent use of steel section instead of latticed girders and frameworks with small elements and tieback which had reduced the space of similar assembly halls before. The lighting effects of a glazed pane between the roof framing had been experienced before at the machine hall of L. Loewe (1882), the machine hall at the Brussels world exhibition (1910), and was further developed by K. Bernhard for the silk weaving mill Michels & Cie. at Nowawes (1912) (Bernhard 1914).

The arrangement of a main hall and subordinate halls for the assembly which had been first developed by K. Bernhard for Straßburg (19) and consecutively

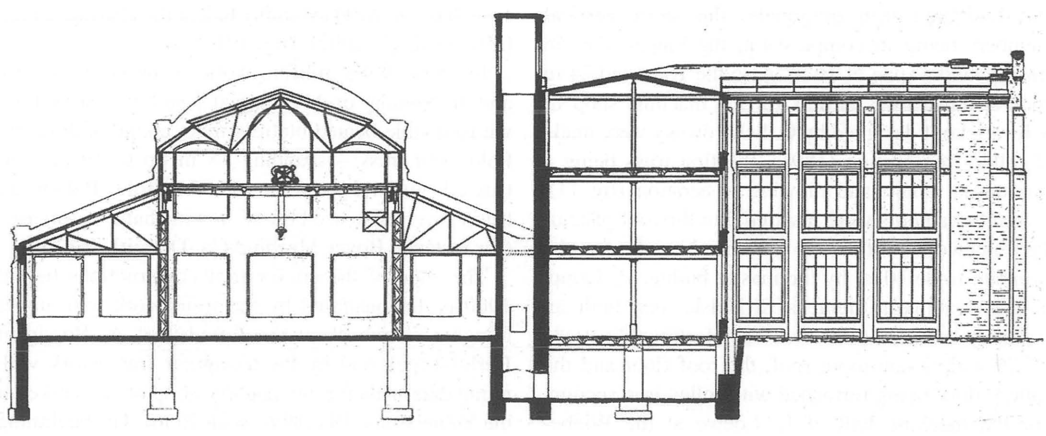
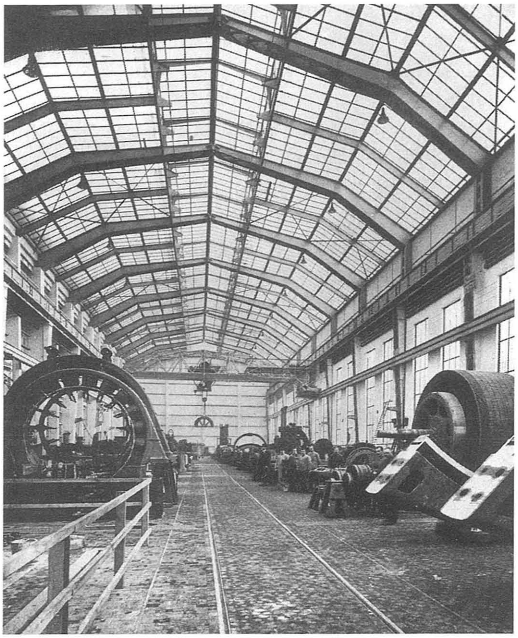


Figure 12
Assembly hall L. Loewe, 1897



Fiure 13
AEG-Assembly hall Hussitenstraße, 1911

in Berlin-Moabit shows the deliberate designing of the construction. Compared with American factories it proves that these principles of construction had already been implemented in the 90's for iron and steel framed structures of machine shops (for instance Newport Ship Building, 1890, and Berlin Iron Bridge Co., 1891, with a fassade of running fenestration, also around the corners).

Floor constructions

The period of seventy to eighty years use of iron columns is closely connected with the introduction of fire-resistent floors, although columns exploded on fire. Despite the danger of fire at production sites and growing standards for industrial buildings wooden floors continued to be in use, and only few combined constructions of beams and iron girders were built.

Also the fire-proof cap vaults with bricks which were used at Schinkel's Bauakademie already 1835, were not introduced for industrial architecture before 1850. We found a modest construction of cap vaults at the glassworks at the Salzufer 4, dating from 1864.

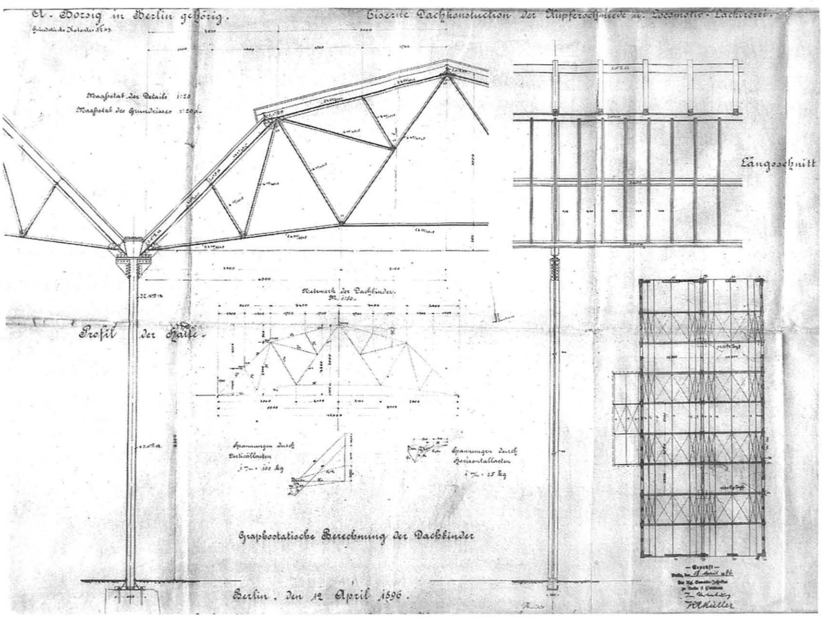


Figure 14
A. Borsig Polonceau truss 1896

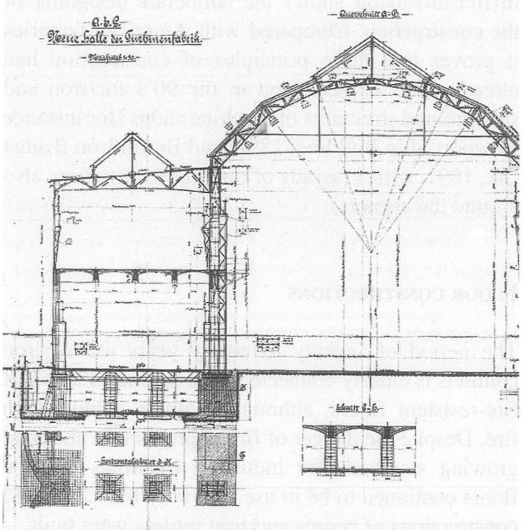


Figure 15
AEG Turbine hall, 1908, cross section

Only in the 80's the cap vaults came more and more in use. Besides the typical inner construction of wooden beams with load bearing I-girders and hollow cast iron columns with capitals the spaces between the I-girders were filled up with flat brick cap vaults which were later on called Prussian cap vaults. The new paint mill of the Beringer factory at the Einsteinufer 65 (1889), the AEG works at the Ackerstraße 76 (1893–96) and the small engines shops by B. Behrens at the Voltastraße (1911–13) were furnished with Prussian cap vaults.

Beam floors across several columns which had been performed at the English docks and storehouses between 1800 and 1839 turned up in Berliner industrial architecture earliest at the storehouse by L. Hesse (1835), at Schinkel's packing storehouse (1832–35), and also at the administration building of F. A. Egells (1847). Possibly these floors have been calculated in neglecting the moment determination by oversizing the load-carrying elements, simply placing beams across two columns, section by section and side by side (Hertwig 1941).

The new floors of the rebuilt Royal Mills at the Mühlendamm by L. Persius (1848) represent a very singular construction. The beams of 3,76 up to 5,03 m length were shaped like a fish belly, in each section they paired two rails which were placed on the capitals of iron columns (Rothe 1849). (fig. 6).

Of equal interest is the construction of a gallery floor with iron girders at the drilling works of the Royal Artillerie shop at Spandau (1855), the joist beams having been replaced at the new building (1859) by wrought iron latticed girders (Wiebe 1859).

The static advantages of enforcing girders by a reverse hanging truss or a reinforced girder were known since the middle of the 30's. R. Wiegmann improved the reinforced girder and introduced this construction together with the Polonceau truss about 1839–40 into the German speaking professional circles. The reinforced girder, usually a wooden beam, was placed on a cast iron column, the bottom being connected to the seating with two slanted tiebacks. This girder could only be performed in industrial buildings where no massiv loads had to be carried (LAB Rep 10–02).

For the smithy of F. A. Egells at the Chaussseestraße 3 a reverse hanging truss was built in 1850. For floors of smaller sheds and steam boiler shops of the Kühlstein factory at the Salzufer 4 plain and double reverse hanging trusses were performed 1882, 1888 and 1893.

Corrugated metal floors combined with iron section girders were not only used for preliminary storage buildings but fixed with cement screed, even for multi-storied factories (for instance Kühlstein, Salzufer 4, 1882).

In the 80's the search for suitable solutions for fire-proof floors was enforced to match the growing standards of fire protection between stories and an improved load support. The building magazines and manuals, amongst others the Deutsche Bauzeitung of the architects and engineers association and the later editions of G. A. Breymann construction manual of the 90's, published a number of iron reinforced block floors which eventually were not carried out because of costs. In our research work we only found very few reinforced block floors in the drawing plans.

The combination between bricks and steel section girders for reinforced block floors which were to improve the tension strength often failed because of technical or structural defects. Reinforced concrete floors following the patent of Monier were more successful. This construction was improved in calculation and performance in the 90's by M.

Koenen. After having developed the ribbed floor (1894) which combined concrete ribs made of I-girders at a space of 25–30 cm with the concrete floor as a whole, he designed about 1895 the «Koenensche Voutenplatte» (vault rib) where the iron elements were placed in the middle of the plate and on top of the double T-flooring system. The final pieces are thus stressed like brackets whereas the centre piece is carried like fixed beams. Like this the ribs could be placed at intervalls of approx. 2 m. Koenensche rib floors (joinery) and Koenensche Voutenplatten (machine tool shop) were performed for L. Loewe at Martinikenfelde (1897 and 1898) for a use load of 1 500 kg and spanning 3 m (Mislin 2002). (fig. 12).

Stone floors with solid plate and enforcing ribs on end or joined bricks were rarely used in Berliner shops. In this context mention should be made of that all buildings with reinforced concrete needed a special building permit. Only on decree of the ministry for public works, on April 16th 1904, standards for the use of reinforced concrete in design and construction of buildings were released, thereby facilitating a building permit (Baltz 1905).

Skeleton structures

Plain iron constructions of the Berliner industrial architecture were not openly performed, but hidden behind masonry walls:

- — 1844–48 Royal Mills at the Mühlendammbrücke (fig. 6).
- — 1878 Tobacco Factory W. Ermeler & Co.
- — 1882 Machine Hall L. Loewe at Kreuzberg (fig. 10).

The factory buildings of L. Loewe at the Huttenstraße (1896–99) mark a turning point in the history of constructions and of industrial buildings. For the three storied building reinforced rib floors, cast iron columns and masonry wall were combined to make a true skeleton building. The outer walls were reduced to piers and apron walls, instead of the hitherto known masonry walls vast window panes were created.

At the beginning of the twentieth century the well known assembly halls by P. Behrens for the AEG at Moabit (1908) and at Wedding (1911) self-assuredly represent the skeleton construction of modern architecture.

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The relationship between scientific knowledge and the building achievements. The evolution of stereotomy in the eighteenth and nineteenth centuries

Giovanni Mocchi

Geometria plure præsidia prestat Architecturæ. These words, taken from Vitruvius work and assumed as a motto by Frezier in the frontispiece of his famous book, can synthetically explain which was the position of the scholars in stereotomy in the period that runs from the appearance of Delorme's «Le premier tome de Architecture» (1567) to the publishing of Frezier's «Traité de stéréotomie à l'usage de l'architecture» (1737–39) which concludes the first and fertile season of treatises on stone building. More strenuously than in preceding works on the subject, Frezier, in this book, supported the idea of the usefulness of mathematics in the development and progress of architecture. The search for the rational foundations of architecture which charecterized a good deal of the French treatises on stereotomy and theoretical studies on architecture starting from Delorme and Perrault, seems to stop with Frezier's *Traité de stéréotomie* where the geometrical rigour of building problems reached its highest peak.

The author was convinced that, a scientific knowledge was necessary for the development of architecture and that such a knowledge could give the opportunity to satisfy new demands without waiting for the consolidation of practical solutions.

Such a convinction, clearly stated in the *Epitre* of his work, clashed with the emerging ideas which tended to go beyond the doctrinal separation between theory and technique. The will to demonstrate the usefulness of reasoning applied to building represents one of the topics of an open debate between the supporters of the necessity of a scientific foundation in architecture and those who wanted to revaluate technique and knowledge acquired through experience.

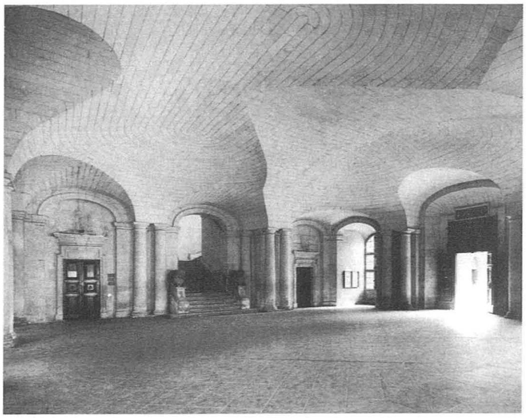

Figure 1
«Hotel de ville» in Arles (1673). Stone Vault of the hall

Against the theses of the stereotomists and especially against Frezier's ideas expressed in the first volume of his treatise in 1737 set Cartaud's *Pensées critiques sur le mathematiques* published in Paris in 1734 where the author stated the uselessness of mathematics for the progress and improving of the Beaux Arts.

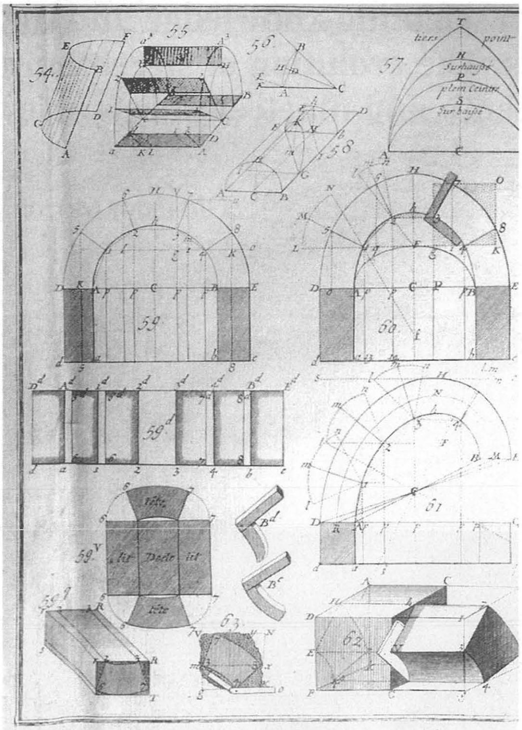

Figure 2
Geometric explanation of a stone barrel vault (Frezier 1737–1739)

The controversy spread and went beyond the theoretical debate: Frezier's work was harshly criticized by constructors because he wasn't able to meet the necessities of the building process.

Frezier's aim was to demonstrate how every situation dealing with the definition of stone structures could be solved by use of geometry but not a word came from the author to explain how his complex geometrical constructions could be of any help to the pratical needs of a building site. Criticism from experts led Frezier to publish a compendium of his work whose title was *Elements de stéréotomie à l'usage de l'architecture*, in 1760 but, like his master Desargues, he didn't succeed in eleborating a synthesis of the stereotomic problem.

The study of the evolution of stereotomy proceeds side by side with the study of how the problem of free stone building is dealt with by the different authors.

During the first period of stereotomy running, as we have already said, from Delorme to Frézier and the works of M. Jousse, G. Desargues, F. Derand and J. B. de la Rue, such a problem coincided with the elaboration of the rules which enabled to determine univocally the form of the voussoirs of a vault. Such rules are of a geometric type but seems to originate from some building considerations deriving from the age-long experience of gothic constructors. These considerations, never expressed in the works of the above-mentioned authors, will clearly appear about a century after Frézier's *tràité* in Adhemar treatise when the transformation of stereotomy had already taken place.

The stereotomists' goal was to find a rational solution, I mean in geometric terms, in order to obtain a building that was *comme une seule pièce*. Their interest was to eleborate rules by which it would be possible to obtain a structure which worked as a voussoir arch; that meant to define voussoirs with joints in radial sequence through univocal geometric construction.

As a matter of fact the acquired experience suggested the best form for every building problem requiring a vaulting. The relationships between the span and thikness of a vault were defined by rules handed on orally inside the various guilds of constructors. In order to determine the thickness of piers, some empirical geometric costructions were used on the basis of the form and size of the vault. These considerations are not dealt with in treatises of stereotomy. In that context they usually debated on the geometrical definition of the voussoirs. Such a result was achieved by geometrical constructions based on the intersection between the intrados surface and the system of surfaces that included the voussoirs' joints.

Frézier was the first to arrange in a system the pieces of information about geometry applied to stone cutting. If we exclude some little investigated works by Hero of Alexandria and Anthemius of Tralles, such a topic had only been treated, mostly with poor scientific rigour, for the last two hundred years.

Frézier deemed it necessary to start his study on stereotomy from the intersection between solids and surfaces and the study of the resulting curves passing on to the description of the methods for representing solids and their sections on a plane.Then he dedicated two of three volumes of his work to the discussion of

various examples of vaulting and to the definition of their respective voussoirs.

His intention to demonstrate the usefulness of a rational process applied to architecture resulted in harsh criticism from those who had to cope with everyday difficulties in a building site.

Frezier's work appeared incomprehnsible to them and not even its figures were of any help because their abstract geometric costructions didn't provide, unless, very rarely, with form and size of the voussoirs.

This event showed two important problems: the inexistence of a common language shored by both stereotomists and costructors which allowed the trasmission and diffusion of the geometric processes.

The second problem consisted in the inefficiency of the two-dimensional representation system of geometric costructions that proved to be inadeguate to convey information graphically.

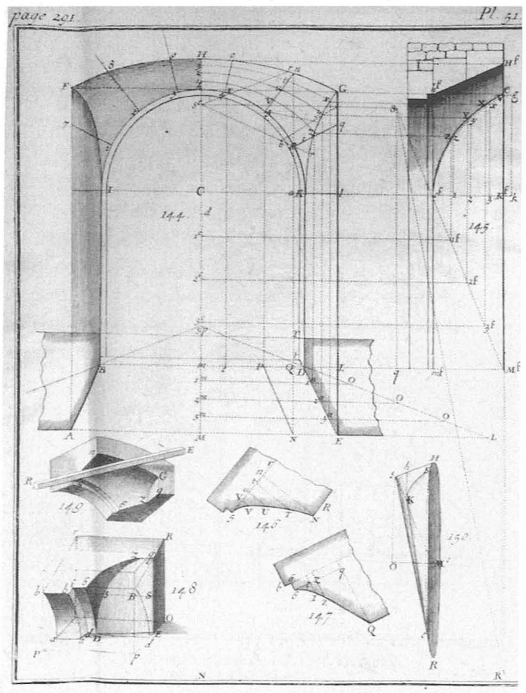

Figure 3
«Arrière-voussure de Marseille». Pl. 31 (Frezier 1737–1739)

Frézier, together with Monge's predecessors, used mainly representations through plan and elevation.

Only in very few cases he introduced the double orthogonal projection wich made the spatial comprehension of the whole construction more precise and complete.

The double orthogonal projection, in fact, would represent one of the basic elements in the maturity of stereotomy.

The distance between Frezier's work together with those scholars who maintained the necessity of a theorectical foundation for architecture and those who emphasized the importance of an empirical knowledge seems even wider if we compare the theorical examples taken into consideration in Frezier's treatise to the level of pratical experience.

The superficial analysis of the compound vaulting especially cross vaulting contrasts with the wonderful stone building showing virtuosic skill that flourished in various areas of France in the XVIII[th] century.

Around the middle of the 18[th] century, as a result of a changed cultural attitude, unquestionable signs of crisis in classic stereotomy started to be evident. The age of Encyclopédie (1751–1772) marked this period of trasformation and reconciliation between theory and practice.

At the some time the pubblication of Abbot Laugier's *Essay sur l'architecture* (1753) represented a harsh criticism against the excessive oddity of stone buildings.

On the other hands on page XIV of his *discours preliminaire* Frezier himself exhorted architects to ostentate knowledge and show indifference towards any kind of restrains.

Abbot Langier's voice wasn't the only one to hurl against stereotomy: J.F. Blondel, too, maintained that a good architect should prefer verisimilitude to the presumptuous arrogance of stereotomy.

The apparence of Diderot and D'Alambert's Encyclopédie started a new attitude as regards the trasmission of ideas in architecture and especially the arts related to building. Any aspiration of theoretical foundation was abandoned and there was a simple record of what had already been acquired. Within the detailed classification of sciences and arts Diderot and D'Alambert's work included also their traditional and empirical aspects. Diderot believed that progress and research could develop only by free diffusion of

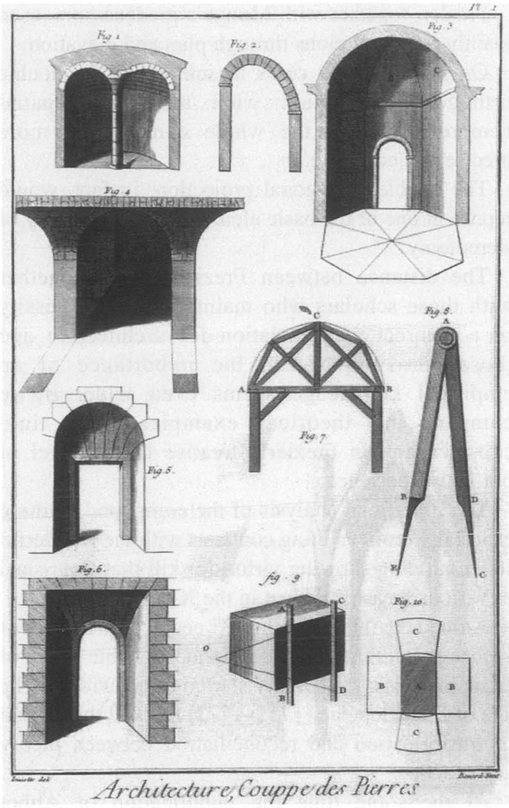

Figure 4
Concise treatment of stereotomy in «Encyclopédie» (Diderot and D'Alambert 1751–1772)

information and the capillary penetration of knowledge.

Stone building was classified among the arts belonging to memory, within the class of natural habits, in the subdivision of Natural History, denying, in such a way, its scientific and rational aspect.

Such on attitude might have been motivated by the fact that the studies on stereotomy had no link with the bulding site techniques and methods which were still trasmitted orally in those year.

Editor of the section of the Encyclopédie dedicated to Architetcture was J. F. Blondel. Though A. Frézier and F. Derand's works were mentioned, the editor showed no interest in stone building at all.

However, it's in the set of figures included in the volume that we can realize that the stereotomists' studies were completed disregarded. As a matter of fact in the illustrations dedicated to stone building, they handly examined some kinds of vaulting and as far as voussoirs' form and size are concerned only flat arches and flat floors were dealt with. There was a conscious refusal to treat stone building in the steretomist's fashion, as if their intention was to deprive it of any importance. If we compare the attention dedicated to woodden ceilings with that dedicated to stone building its evident a clear partiality in favour of first technique. As regards woodden ceilings the difficulties of the geometric treatment is certainly comparable to that which characterized the works on stereotomy. This can

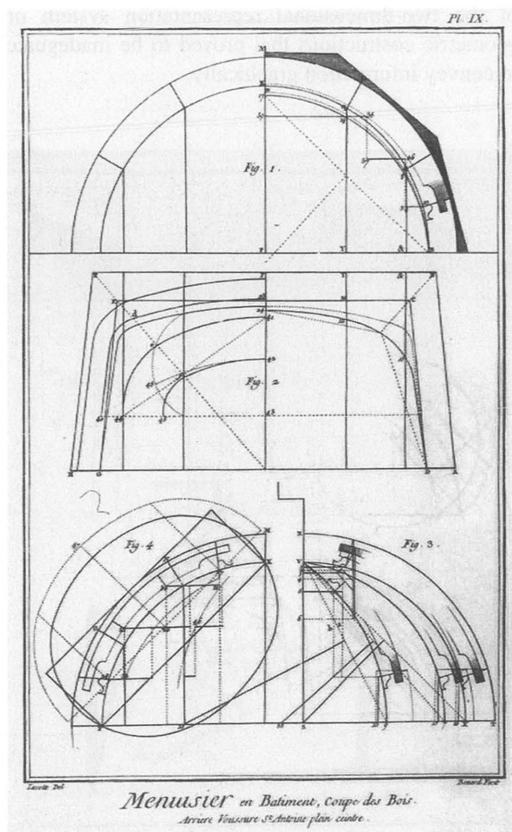

Figure 5
Geometric explanation of woodden ceilings in «Encyclopédie» (Diderot and D'alambert 1751–1772)

be seen both in figures and in their relative explanations. In Frezier's works the results of stereotomic constructions had been elaborated for both stone building and woodden ceilings as the title itself expressed. On the contrary in the Encyclopedie only the interior carpentry, called *menusier en batiments* seems to keep a close connection with geometry. In the text, even less impotance is given to the problems of statics, in fact, one single figure and very little explanation are dedicated to the problems of equilibium of arches. Probably no editor was able to give, in the little space available, any explanation about subjects being animatedly dealth with in the accademies in those years.

In Frezier's treatise a whole part had been devoted to the statics of vaulting with the intention to define what the thickness of piers, necessary to carry the thrust of vaults, should be. In doing that the author used the already known conclusions reached by De la Hire and Belidor.

The publication of the volumes of the Encyclopedie, as we have already said, marked the crisis of classic stereotomy and led to a general reflection about stone building which, in the dawning of the XIX century, was heading for a deeper awareness of its nature. Gaspard Monge gave the necessary stimulus; in his work he succeeded in collecting all the conclusions and demostrations already elaborated by mathematicians. In 1800 decriptive geometry developed and proposed the double orthogonal projection, which permitted an exact knowledge of the three-dimensional space and its correct representation on a two-dimensional plane. All that meant the end of the difficulties related to the explanation and representation of stereotomic constructions.

The first author who could take advantage of such conclusions was J. B. Rondelet whose works (1802–1817) have been widely studied.

Nevertheless the last stereotomist gave a better systematization of the knowledge about stone building and made its intrinsical problems evident. Around 1750 the crisis of stereotomy involved not only its theoretical aspects but the whole practice of

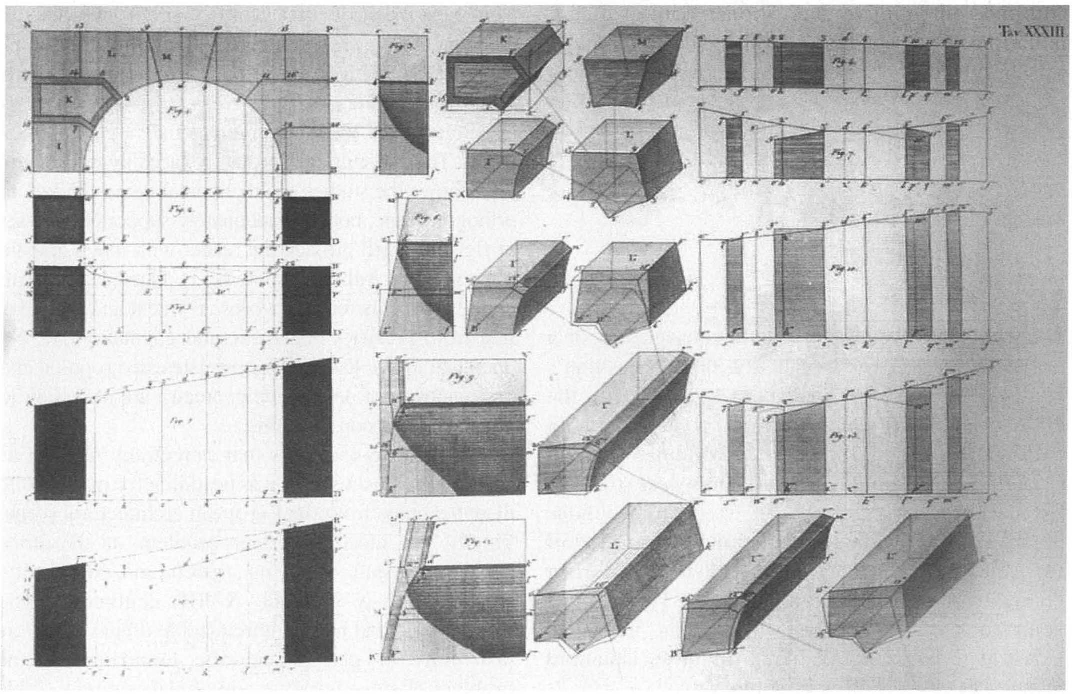

Figure 6
Study on different stone barrel vault in Rondelet (1802–1817)

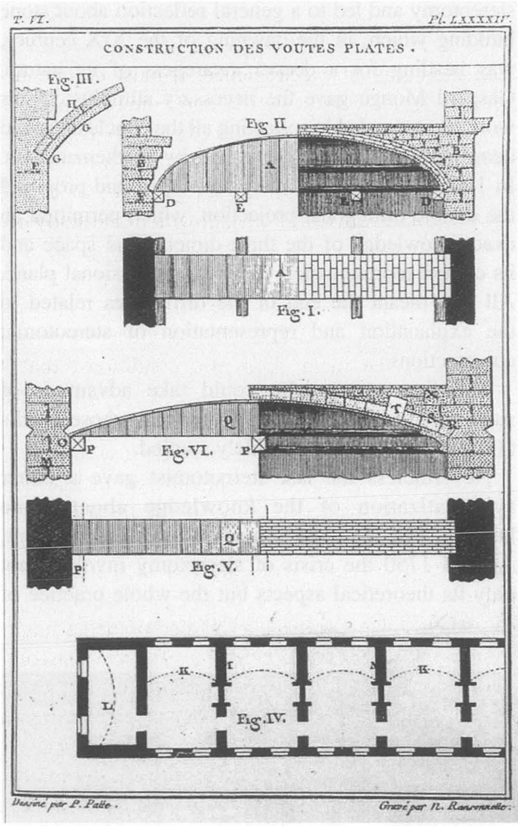

Figure 7
Roussillon's vault in Blondel (1675)

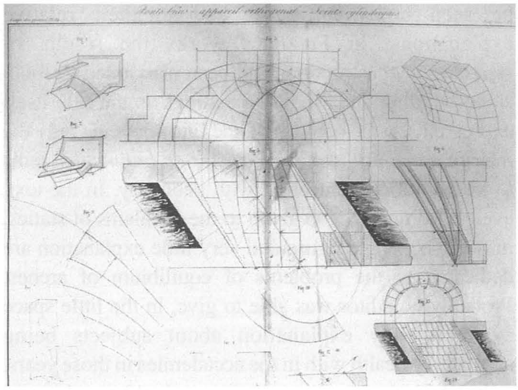

Figure 8
Oblique running bridge's example with orthogonal device (Adhémar [1850 ?] 1870)

stone building declined also as a conseguence of a change in taste. The popularity that Roussillon's vaulting enjoyed in those times thanks to the diffusion of Abbot Laugier's work, contributed a lot to the falling out of grace of stone building.

During XIX century these structures were still used for infrastructural works such as railway oblique bridges. These buildings had to follow the layout of the railway line so they might either cross a river obliqually or have a curvilinear tracing. The acquired experience of constructors, more than innovated techniques, could be profitable in these situations where a technical skill was required.

In 1870 the sixth edition of J. A. Adhémar's work *Traite de la coupe des pierres*, included in a wider *Cours de Mathematiques à l'usage de l'architectes* was published. Unfortunately I'm mot able to give you the exact date of the first edition but I think it must not be prior to 1850.

Almost half of this work is dedicated to the discussion of several problems related to the building of an oblique-running bridge. One of the major problems of such structures is the necessity to prearrange a building device in order to avoid the risk of a void-thurst. The difficulties is brillantly faced by the authors who shows the studies of a helicoidal device and of an orthogonal one, both are adequately supported by a set of figures which provide the reader with much graphic information. Adhémar's work is carried out with lucidity and coherence, his prose is fluent and effective, free from Frezier's bombastic and dogmatic tone. No demonstrations, lemmas or postulates are proposed and basic notions of descriptive geometry are necessary to understand his constructions.

This treatise witnesses that stereotomy reached its full maturity just when it was headding for its complete disappearance from the European architectural scene. Finally the most important problem of the stone building appears in all its aspects and complexity. During the XVII and XVIII century classic stereotomist had had an unrealizable dream about the possibility of giving scientific foundation to the problem of stone building and of elaborating a single solution which could satisfy any request concerning formal, building or static aspects.

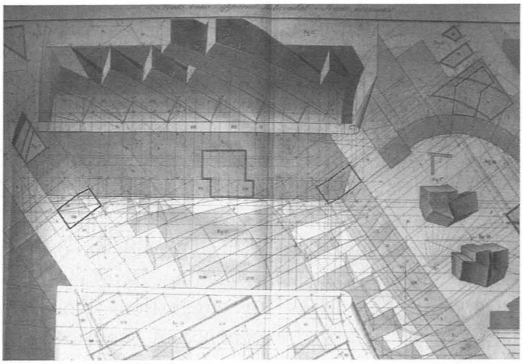

Figure 9
Oblique running bridge's example with helicoidal device (Adhémar [1850 ?] 1870)

On the contrary, in his work, Adhemar pointed out, more than once, that stereotomy couldn't be considered as an exact science. It must be intended as a series of both scientific and empirical notions: a fascinating mixture of abstract concepts and references to the physical reality of the building problem. In the proposition 844 the author clearly stated that the difficulties dealth with in the study of a complex situation such as the building of an oblique-running bridge, derived from the incompatibility of the limitations and considerations of mechanical, building and geometric nature. As a matter of fact, as regards the main geometric conditions, that is the absence of acute-angle voussuoir which had represented an implicit rule also in classic stereotomy, it was possible to obtein either voussoir with double-curved joints but their cutting proved difficuilt or joints with inclination contrary to the theories of the mechanics of arches but that led to a subsequence rotations and to the appearance of dangerous void-thursts.

On the other hand the existence of acute angles could cause a localized braeking of same voussoirs' edges while, wanting to privilege the setting of the voussoiurs, that could lead to an unexceptable formal solution. Previosly, in proposition 373, Adhemar had explicitedly introduced the structure of stereotomic problem; according to him, it is composed of five faces: 1) the choice of projetcion plans; 2) the choice of the thickness of vaults and piers', and then of the

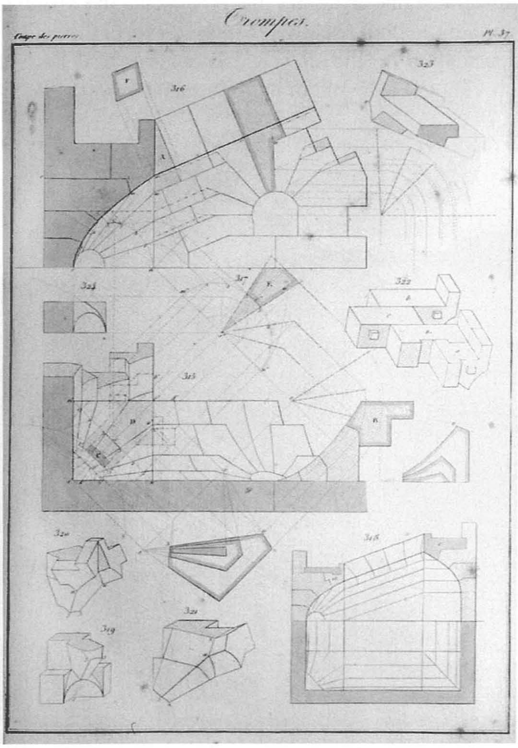

Figure 10
A very complex stereotomic's problem: the «trompes» (Adhémar [1850 ?] 1870)

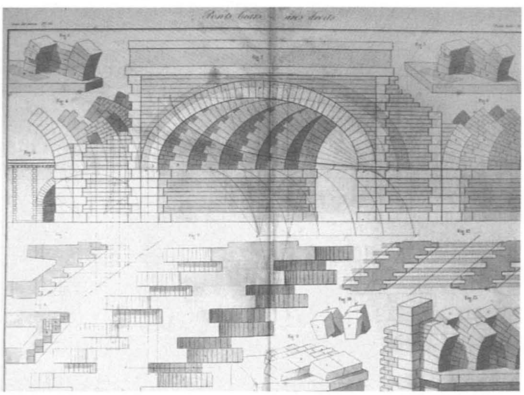

Figure 11
The third construction device for oblique running bridge: the «arcs droits» device (Adhémar [1850 ?] 1870)

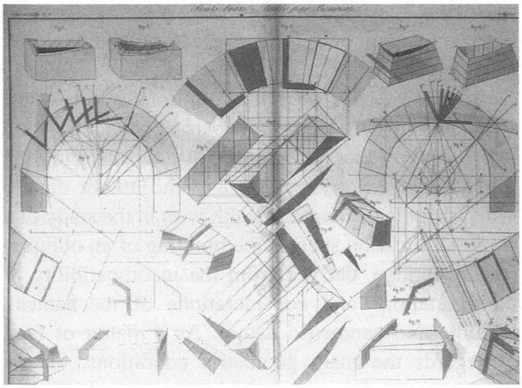

Figure 12
Use of barrel vault device in a oblique running bridge (Adhémar [1850 ?] 1870)

whole device; 3) the definition of the joints surfaces; 4) capsizing and development of the surfaces of the different joints faces and 5) the tracing of the joints on the voussoirs and their cutting. As we can see, vaults thickness and building device were quantitative and qualitative variables that constructors had to fix in advance.

The continuous references to mechanical, geometric and building problems is emphasized, in some cases, by the personal intervention of some constructions who the author appeals to for empirical help when explanation of geometric constructions and static reasonings are not sufficient. That is the case of the directions about stone cutting and about the form to give to some very complicated voussoir. Adhemar's reader seems to be already dealing with the carring out the building of a stone vaulting. He is probably an expert who looks for suggestions when he lacks the consolidated experience of generations of constructors.

The battle of the supporters of classicism against the use of stereotomy in the Architecture didn't prevent stone building from resisting even if in rather different form up to the end of the XIX century. When the theories of eclectic architecture flourished and the traditional architectural inheritance of the different countries revived, stereotomy enjoyed some moderate fame again. By that time, being the world of building techologically changed, every theoritical speculation on the subject had come to a dead end proving to be devoid of any sense and aim.

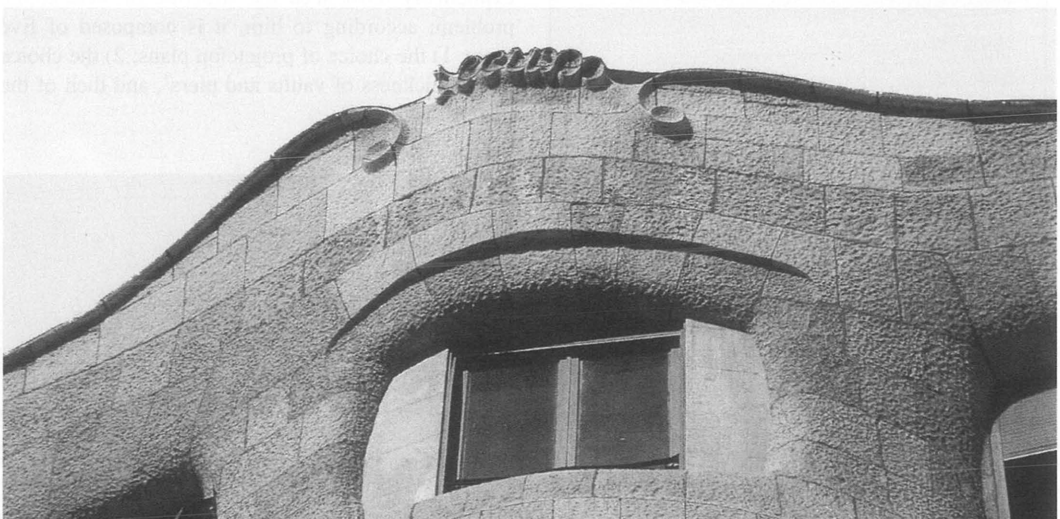

Figure 13
Antoni Gaudì. Milà's house in Barcelona (1906–1910). The stone covering of the facade

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The use of pointed vaults and side shaped walls for a new structural form consequent to one Renaissance original design

Nanni Monelli

A COMPOSITE ANTHROPOMORFIC RELIQUARY BASILICA

The beginning of the building of the Basilica of the Holy House at Loreto dates back to 1469 but, if archive sources do not supply the name of the designer engineer, it seems to be certain that the first project is to be assigned to Francesco di Giorgio Martini.

However it is sure that besides Francesco, many other world-famous men such as Baccio Pontelli, Giuliano da Maiano, Antonio da Sangallo and Donato Bramante worked there.

In any case, the important considerations that may be made about the building are so many that they justify the definition of an extremely original and interesting church, even though in the wide field of the Humanistic architecture.

It is to be pointed out indeed the fact it is a reliquary basilica, having been built to keep and to honour the Room of Mary, the place of the Annunciation and, before, of the Conception of the same Mother of God, after being transported here by the Crusaders from Nazareth in Palestine, to save it from certain desecration and destruction. A reliquary church that, having to protect a unique value for Christianity, destination of a great number of pilgrimages from all over Europe, wanted to show it in the best position for the aesthetic and philosophical sensibility of the time, that is in a central position. The Room was not a small building structure having

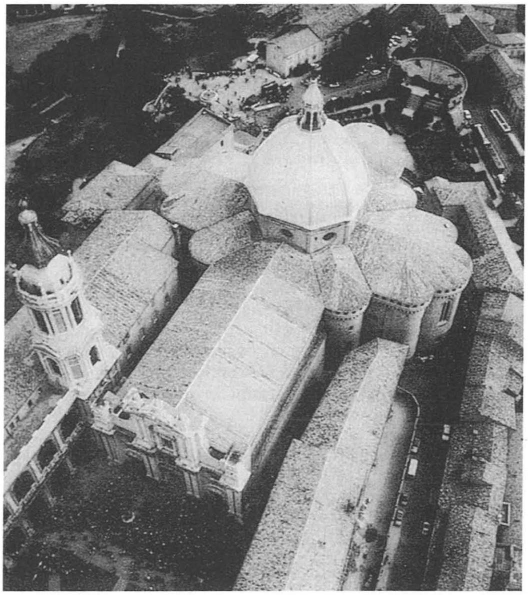

Figure 1
Bird's eye view of the Basilica

6×8 m external proportions, that became 6×11 m, when it was completed as a little church, with a height of 7 m at the ridge of the roof. These values have been rounded up to the metre to give an account of the volumes, considering that the marble covering prevents from making accurate measurements of these values.

The immediate consequence of this reality was to enclose the top of the hill, being unthinkable to dismount once more a structure that defined a holy space, also after the transport. The Holy House is still today inside the Basilica as upon a hill, a condition with some implications, being the hilly ground upon which it rises, clayey and rich in waters.

Furthermore the building was to allow the reception of large quantities of faithful men during the liturgical services having the heart in the relic.

Observing the plan of the holy building, the project is to be considered made in 1469; we may clearly see that the same plan has a composite shape, a fully Renaissance form, theorized by the best men of the period, first of all by Francesco di Giorgio, since the date of the beginning of the Treatises is to be fixed around 1479, but taken again by Leonardo da Vinci —cod.B 24r, 35v, 52r, 55r, all drawings belonging to 1490 and cod. Atlant. 235v, to 1510, even if only one example of such typology was really built just in the planning period, the Loreto Basilica.

While St. Peter's in Vaticano in Rome has become a composite plan Basilica by means of following additions, after having been erected according to a central plan, such uniqueness may be explained with the technical and constructive difficulties met in the practical realization of the spaces. We can find a confirmation of this assertion in the Cathedral of Pavia begun twenty years after the Basilica of the Holy House, architectural structure that, according to P. Fugazza's (1497–1519) scale model, was to be composite, but that was never completed and is still today under restoration, notwithstanding the series of the previous interventions. It was a church planned by highly skilled men such as Donato Bramante and Amodeo, a church that could enjoy other experiences, and, what is more, it was built in a plain land and was not to enclose the top of a hill in the middle.

The choice of the constructive composite plan at Loreto allowed to facilitate the liturgical customs such as the processions to visit the Room, holy space and last aim, and to realize a deambulatory around the hill with the Holy House.

At Loreto furthermore the Church rises according to a plan having an anthropomorphic proportionment, as it clearly appears superimposing the design by Francesco di Giorgio Martini f 42v, also enhancing from this point of view the aesthetic and philosophical aspirations of the time.

The building taken into consideration under the constructive outline appears to be an application of a modular notion of construction, that certainly derives from Gothic experiences, but that surpasses them for rationality, for organization of the parts, for the co-ordination of what was produced, a whole well expressing the technical spirit of the time.

The modular choice is motivated by the following technical requirements: it is mainly an expression of a way of planning and building based upon the use of proportions, simple and effective means to express different forms that may be taken back to the same family.

In large and very crowded yards the use of proportions made up the impossibility of the ubiquity of the works manager and contemporaneously exalted the abilities and the responsibilities of the single teams, who were proud of the work they realized. Modules and proportions therefore were useful for the management of the yard, but they were also considerable facilitations for the men who had to link different parts among them, such as the series of pillars,the scanning of the vaults, the behavioural homogeneity in the different elements that conjugate the one with the other, just as the terms of a proportion, so as to realize a functional and feasible whole with few uncertainties. Therefore there was the necessity of simplifying the building of a very complex volume as a composite church was, and this was attained with structural solutions statistically and constructively proved.

This way of acting, besides having economic consequences on the management of the yard, had the biggest effect of making work human, responsible in the personal autonomy, expressing Christian values and rules.

Renaissance plan with pointed arch vaults and pointed arches and outward vertical shaped walls

The other choices follow from these premises. Only at a first brief survey the Loreto experience seems to be out of time, since some parts recall in an unmistakable way the Gothic elements of a former and far period of time. Therefore just for the beginning date, it appears a much more unique than unusual Renaissance solution looking like an

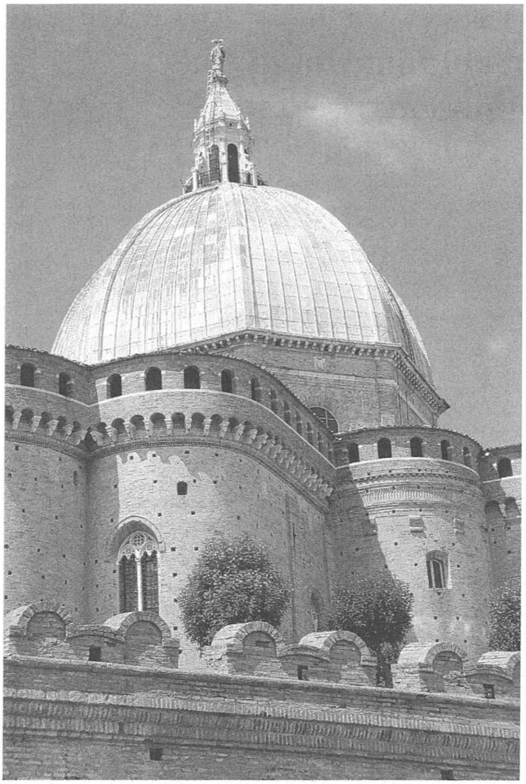

Figure 2
View of the north-east apses outside the Renaissance walls

application of an architectural style according to a Linneo classification.

These aspects may lead to highly deceiving conclusions, if we think that near Gaiole in Chianti there is a church erected in 1540 by the Ricasoli family, called St. Peter in Avenano, having Gothic vaults as those at Loreto. Hence the Basilica of the Holy House may boast of many originalities, but certainly not that of being a structure with Gothic forms realized in the Humanistic period.

We may remember here the work of Bernardo di Matteo Gambarelli called the Rossellino at Pienza in the rebuilding of the Cathedral (1459), the experiences of the Logge del Papa by Antonio Federighi (1460) and the Church of S. Maria in Portico in Fontegiusta by Francesco di Cristoforo Fedeli (1480) both in Siena, and at Bosco ai Frati the church of S. Francesco, in the convent of S.Bonaventura, a work by Michelozzo di Bartolomeo (1434) and the interventions of the same author in the Dominican Church of S.Marco in Florence (1436–43). All these works together with Rossellino's experiences at Pienza can be considered the bases of the beginning of the Loreto construction. Rossellino was fundamental.

If from the examination of the vaults we move to that of the outward wall structures, the Renaissance thought shows itself in its fullness. It is evident indeed the influence of the new knowledges about the defensive works not only for what regards the external aspect that is to communicate the feeling of a sure place, foreshadowing those that will develop in the Room at the level of Christian faith, but first of all at the level of the structural strength of the building. In fact at Loreto we find the experiences made in the military stronghold towers, that were to rise in an advanced position on difficult grounds of uneven natural places.

The stronghold towers of the circle of walls at Casole d'Elsa and the Fortress of Sasso Corvaro that encloses inside an old tower, may be given as an example.The same experiences have been here re-elaborated and practically used to be resistant to the horizontal thrusts not due to blunt instruments but to those of arches and vaults.

From the examination of the techniques to the reasons of the choices

Wanting to build a church of a maximum length of 100,8 m, a maximum width of 73,4 m at the transept and an external width of the nave of 28 m, they had to resort to experimented techniques because this was required by the foundation ground and the orography of the place. The light structures typical of a Gothic architecture well become to a treacherous ground.

With the same building typology it was possible to contain the side thrusts and hence the thickness of the buttress structures. The thrust of an arch is in fact proportional to the load, to the square of the light, while it is inversely proportional to the rise thought as the height of the crown with respect to the springer plan.

We are of the opinion that the main reason of such a choice is to be found in the necessity of the covering

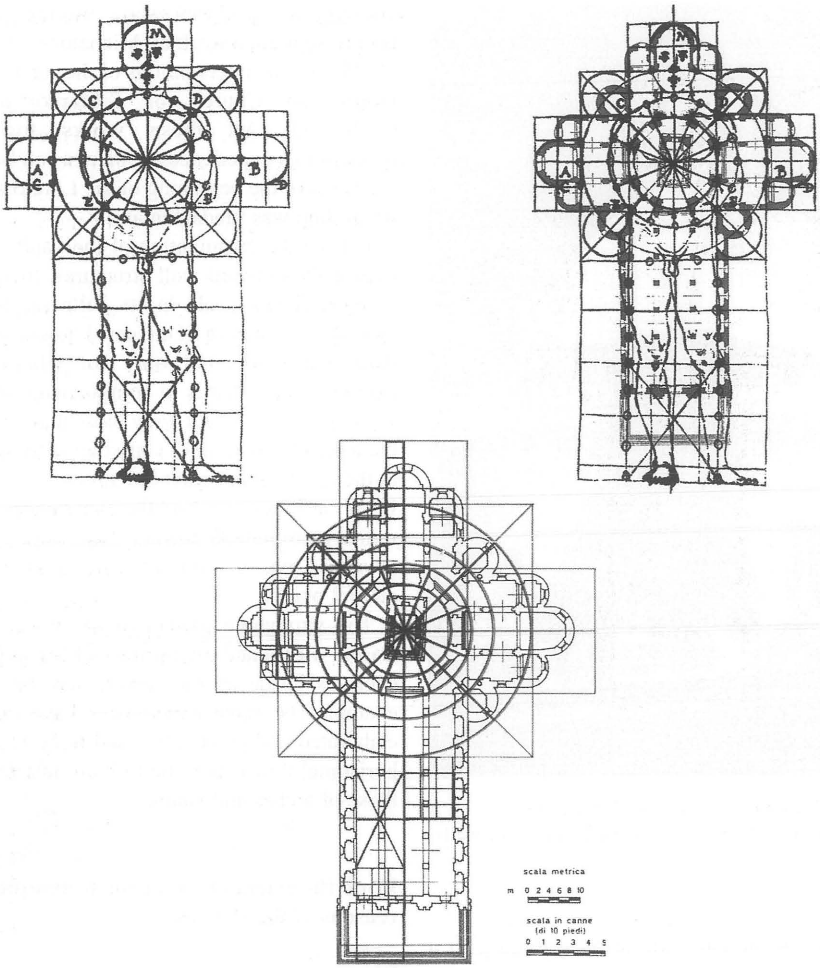

Figure 3
To the left Francesco di Giorgio's drawing f 42 v, to the right superimposition of the plan of the Basilica to the same design and below partition in modules of 10 piedi romani and multiples of 3 and 4 canne of 10 piedi

of the deambulatory with vaults that could conjugate harmoniously with the side aisles ones of the nave and with those side ones of the transept, as to create an annular way around the central body that was to intersect the cross series of the central vaults at a superior height without any problem.

Then there were purely geometrical reasons to be considered. The deambulatory is in fact as wide as the side aisles either in the central body or in the transept divided for the root of two «sorda radice», according to Francesco di Giorgio's terminology, which obliges to give up to round arches, not being able to adopt piers out of proportions and beginning and terminal arches strongly depressed.

At Pavia the problem was solved doing without a deambulatory with vaults at the same level as those of the side aisles, solution that with the lack of a simulacrum in axis with the cupola, allowed to give a better soaring to the central body. Furthermore to improve the statics of the building there was added a

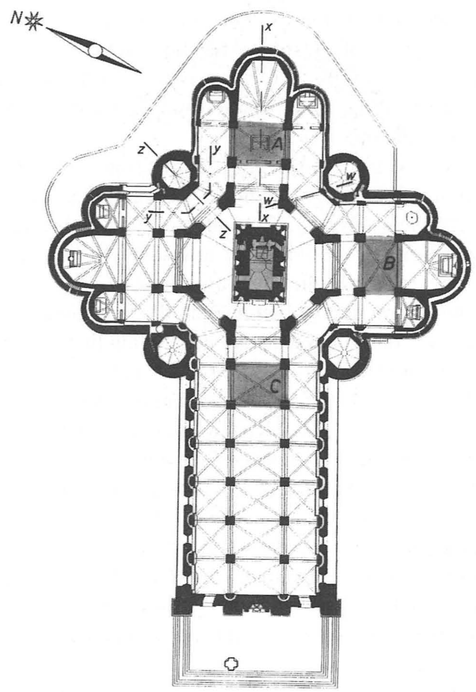

Figure 4
Plan of the Basilica referring to the following drawings

Development and Renaissance use of Gothic structural elements

However the structure of the Loreto Basilica shows that the solutions, even if Medieval,have been submitted and adapted to the new Renaissance spirit.

The first element that immediately attracts our attention looking at the series of the vaults is the use of piers as compensation parts to realise the same succession of vaults and the mutual contrast of the thrusts from the central nave to the side aisles along the external walls. The piers are based upon pillars along the inside perimeter of the cross of the central nave at a level of 1220 cm from the floor of the deambulatory. To this end two examples may be given: the Pienza Cathedral experiences and the Logge del Papa in Siena (1462).

The cross vaults are then with such rises as to have bays with double curvature so projecting and shaped as to reject any Medieval likeness.Also the vaults «a creste e vele», if we go back to Medieval experiences, rely on the fast development of the Florentine realization: the old sacristy of S.Lorenzo as the most radial vertical wall at 45° as to the axes, non existent at Loreto.

However this was a seriously penalizing solution that did not damage S.Siro's, being here different the needs which were more ideological-aesthetical than functional for the liturgy.

The necessity then of having a series of vaults going from the centre to the perimetrical wall, a geometrical limit, forced to definitively reject the round arch on behalf of the pointed one, more adaptable in the shape than the first, being able to vary arches and proportionment of the springers or in the case of the terminal solutions the possibility of using more suitable arches to transmit axial loads.

There is another reason, which is very important about the use of vaults and pointed arches:it is the possibility to find in the Marche and its surroundings labor force skilled in preparing such structures.

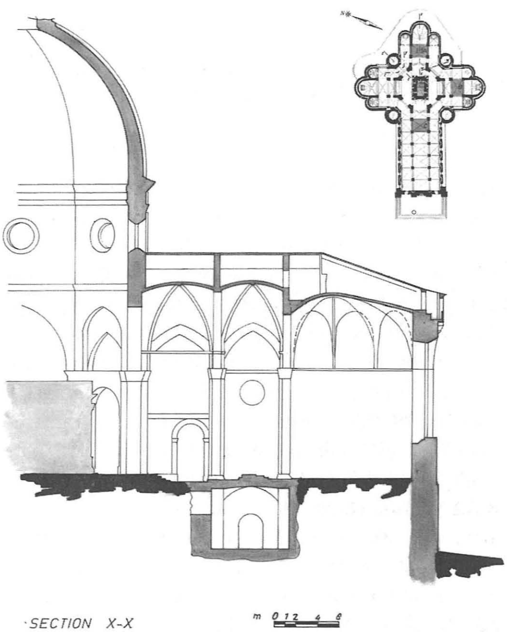

Figure 5
Longitudinal section of the apse

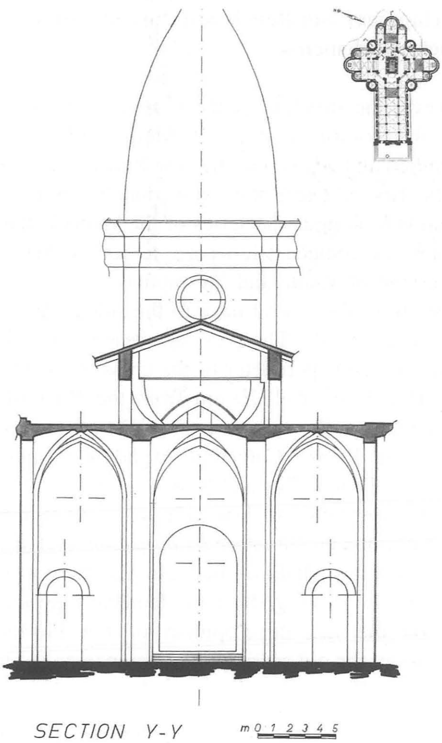

Figure 6
Section on the barrel pointed vault and on the adjacent cross vaults. You can see the spurs and the rafters in the loft

distant experience, and above all, the Pazzi Chapel by F.Brunelleschi, the apse of S.Francesco a Bosco ai Frati by Michelozzo and the less famous work of an unknown technician of the Grancia of Cuna near Monteroni d'Arbia. The same experiences improved and adapted to the specific needs were taken again by Donato Bramante in the Cathedral of Pavia. It is also very interesting the use of the big niches along the side walls of the central body made to lighten the loads, to make the construction easier, to spare building material without damaging the resistance and the endurance of side thrusts.

It is also very important to notice that these big niches have domes spanning a semicircular area instead of pointed arches, lacking any reasons for this kind of construction. In short they research a behavioural homogeneity not only limited to the structural homogeneity of the Gothic architecture.

The big niches and the floorings of the loft corresponding to the vaults of the side aisles, planes upon supports that stiffen the horizontal planes in connection with the outward walls, besides opposing the thrusts of the vaults in the central axis, are a proof of such a laying.

Rounded arches or depressed arches are constantly used in the planes placed under the trampling floor of the Basilica, where, lacking the ground for the shape of the hill, we should resort nowadays to the filling material to realize the same trampling floors.

The central cupola by Giuliano da Sangallo is such as to have octagonal plan and proceeding that, like the one by Brunelleschi at S.Maria del Fiore, recall the Gothic Architecture. In the four corner towers where the old sacristies are lodged, at an intermediate level, there are octagonal rooms in the inside plan having cloister vaults or rounded arch dome vault, that have nothing to do with a Medieval proportionment Proceeding to a comprehensive examination of the building, the main peculiar aspect is a structure in a plan closed by vertical walls that in the less far areas from the main source of the horizontal thrusts, the cupola, has an arcuated concave shape working with the four towers. This was the solution chosen to contain the depths of the masonries on the same results.

ANALYSIS OF TYPOLOGIES AND OF THE WEB COURSING OF VAULTED STRUCTURE

The Cross-Vaults

The vaults that will be described here for what regards their web are those upon the axes of the plan because those of the perimetrical side aisles, either of the central body or of the transept, are all floored in the upper part, having been filled the supports with inert materials; they cannot be surveyed because all the intradoses of the vaults in the basilica are plastered or decorated. Furthermore at Loreto there two typologies of web coursing of the vaults on the central axis: **a**) that of the vaults on the transept and in the apsidal area and **b**) the one of the seven vaults of the nave.

a) They are vaults starting with rows of bricks symmetrically placed under the edge of the extrados, creating together an angle that is of

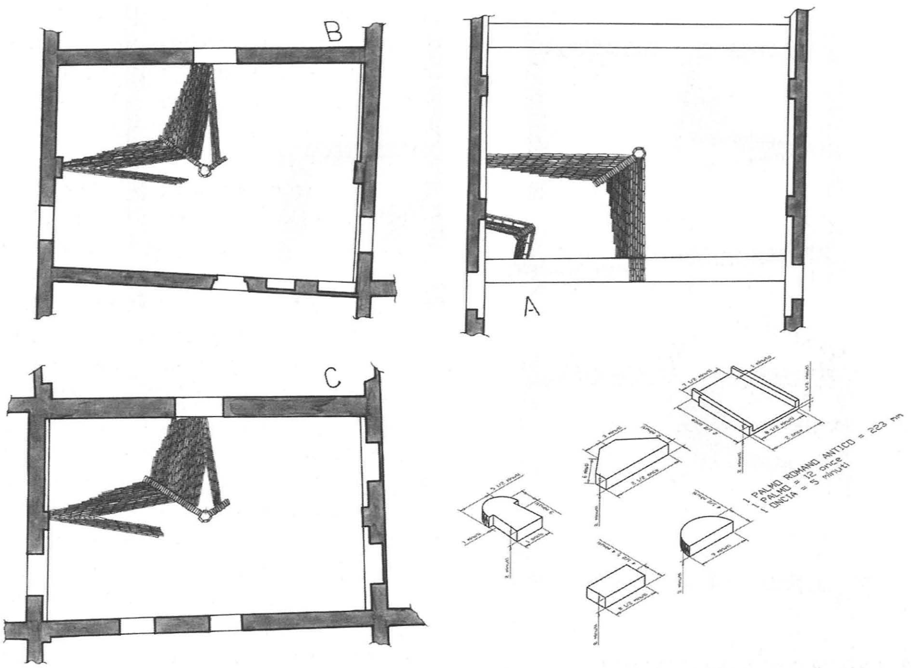

Figure 7
Radial section on the north-east tower. In the detail above it is evident the shape of the buttress contained in the structure

15° for the vaults of the transept and of 20° for the apsidal arm according to the herringbone pattern. Being the vaults 30 cm deep, the bricks are mostly placed in a pseudovertical position, that is radial. These vaults, as well as those «a creste e vele» have been built with a wooden centering for the crests in conformity with a strengthened technique, since they could have been built thanks to the herringbone pattern as partly self-bearing bays. The self-bearing of these bays comes from the fact that the rows of bricks are placed at 7,5° or 10° as to the ridge of the roof and from the position of the bricks radially placed upon inclined bed. Every row becomes an arch between the impost arch and the diagonal arch, balancing their thrusts upon the diagonal ribs, proceeding continuously in the four bays after choosing a course of construction. Remnants of shaped bricks as well as ribs of these bays let us suppose vaults built upon shaped ribs in baked bricks.

b) These cross vaults are different from the previous ones for the much higher rise and for the apparatus. All the rows of bricks are in fact placed in a parallel way to the axis of the ridge. The vaults are about 30 cm deep, being the bricks placed radially and some of them projecting from the extrados for a half of their length. They have bricks reinforcements of 13 cm in the supports cooperating with the vault. The rises measured on the intrados between the key of the vault and the key of the arch of impost of the six modules along the axis of the nave are included between 120 cm and 130 cm against 91 and 93 cm of the rises of the two cross vaults of the south side of the transept, going from the cupola towards the outside, and similar values are in the apsidal east area. The comparison is made among vaults that, while having a different position, have the same module, shape and dimension of the covering area in the plan.

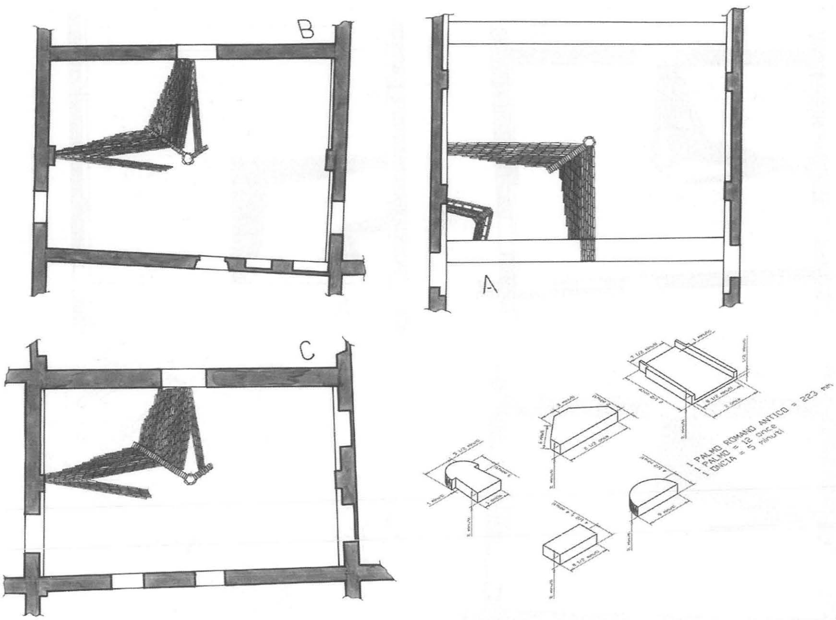

Figure 8
Apparatuses of the cross vaults A, B, C and shapes and dimensions expressed in Renaissance unities of the bricks and special parts in baked brick

The data above mentioned show that the two families of vaults accomplish different statical functions, of mutual contrast, the second ones conjugate with the front of the Basilica, the first ones with the vaults «a creste e vele» at the end. We do not examine the cross vaults of the side aisles, because the extrados is floored on the supports, so it is not possible to have enough elements of judgement. It is however to be pointed out that also all the terminal vaults of the side aisles of the transept are «a creste e vele», while in the apsidal area they are cross vaults for obscure reasons.

The vaults «a creste e vele»

The name given to this typology of covering may be the object of different opinions. Here this name is used and not the one of vaults «ad ombrello», ribbed vauls, because this name as well as the one of the vaults «a lunette e vele» well expresses the true structural form of the covering of all the terminal chapels of the transept and of the choir with the only exception of the two side chapels of the apse which on the contrary have cross vaults. These names lunette,creste e vele are Renaissance words.

These vaults are characterized by a surface of the extrados very different from the intrados. In fact if the intrados is made by a couple of radial groins creating a pointed arch with decreasing rise going from the outward walls to the key of the vault, the extrados is made by depressed arch vaults between crest and crest.

In the apparatus as well as in the typology of the extrados and of the supports the likeness with that of S. Francesco a Bosco ai Frati is noticeable. The difference between the two vaults is in fact in the lower bays that Michelozzo made as rounded arches, which made him have a rise bigger than the one existing at Loreto.

In the extrados of the vault which seems to be the last realized, that is in the north arm of the transept, there is a brick curb that for its position and form appears to stiffen the superior part of the covering with depressed vaults against the twist.

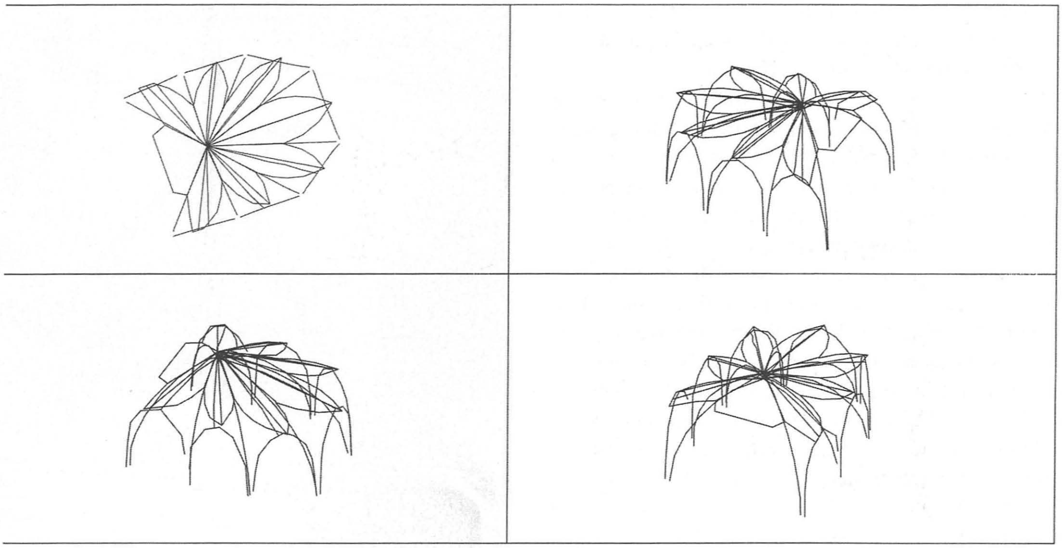

Figure 9
Survey of the apse vault «a creste e vele»

The crests are realized on a shaped brick ogive in the pattern of a mushroom with radially placed bricks so as to create a vertical face, «cresta». For the domes of the extrados the web coursing of the radially placed bricks is in rows parallel among them and to the axis of every little vault. The depth of the vault «a creste e vele» reaches about 35 cm and they are made with wooden centering under the crests and a large use of lath.

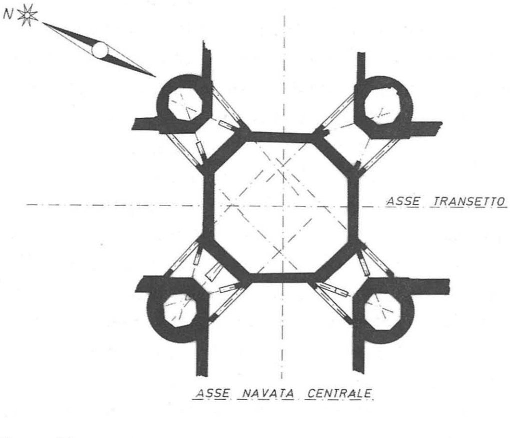

Figure 10
Schematic section of the drum with the indications of the spurs and the rafters and with the indication of their direction of action

The pointed barrel vaults with lunettes

These vaults are perhaps the most interesting ones because of some geometrical aspects and of the contribution they give to the statics of the building, even if not in a direct and evident way.

We particularly refer to the arches of impost at the end of the vault that do not appear in conformity with the right angle, being the pointed profile of the impost inclined as to the axis of symmetry of the barrel so that the directions of the two terminal arches are converging on a point of the symmetry axis perpendicular to the axis of the vault. This point is on the vertical axis of symmetry passing in the centre of the tower adjacent to the vault. The solution is not casual, since these arches have as a superior delimitation some concave spurs starting from the octagon and,as the arches, they have a radial direction with respect to the towers. The wall defined by these

arches accomplishes a double function, the second of which is more important than the first. The arch at its end fully stiffens the vault for the action of cutting, but, what is more, the whole of the lower arch and of the superior one, as a buttress of Gothic memory, contrast the thrusts of the cupola. These thrusts for the presence of a transverse barrel pointed vault could not be otherwise unloaded on the perimetrical parts fit to this purpose. The barrel vault was built with lunettes to allow large openings at the base of the octagon. This open surface was required by the aesthetic rules of the time that wanted to enhance the perspective from the various corners. Contemporaneously discharging arches inside the masonry were useful to the statics of the building. The excellence and the originality of this solution may be appreciated, comparing it with the one proposed for the project of the new S.Petronio's in Bologna,»Imbocco del Peribolo» in the XVI Century drawing, Arch. Of the Fabbriceria, Bologna, arm.V.

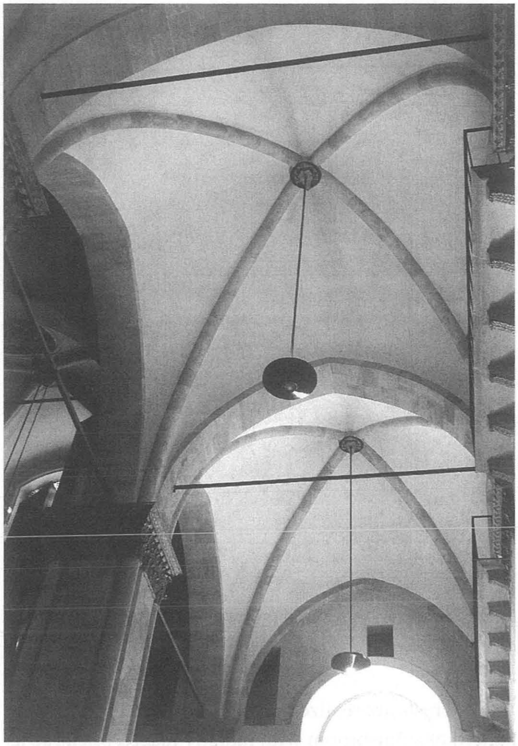

Figure 11
View of the inside with the cross vaults of the side aisle

The Cupola

At Loreto the Cupola was surely built according to the «concinnitas» rule largely diffused by L. B. Alberti.

The previous design lets us think of a different solution, a hemispherical vault that may be found in the Treatises by Francesco di Giorgio as in the anthropomorphic drawing f 42 v of the same author,that is considered the plan of the Basilica of Loreto.

With the hemispherical cupola the profile would have recalled that one of the central plan building of «La Città ideale», Tables at Urbino and Baltimora by unknown author.

However it is certain that the actual cupola was erected by Giuliano da Sangallo (1499–1500), with a little thrusting profile, only two iron chains of 3 × 10 cm for hoping. The cupola seems to be designed staring from the intrados proportioned with bays along the main axes with a beam equal to 2/3 of the circle inscribed in the base octagon and a centre equal to a 1/12 of its diameter, over the cornice crowning the drum. This last one was built by Giuliano da Maiano in conformity with the proportionment of the drawing c 41 r by Francesco di Giorgio.

As little known as it is, the cupola has a spinapesce —herringbone— pattern apparatus according to Sangallo's style. For these peculiarities it is connected to the covering of S.Maria della Pietà at Bibbona, work by V. Ghiberti and R. Tripalle, while the spirit and the values are well expressed by the frescoes situated on the left side of the nave of S. Polo in Rosso near Gaiole in Chianti.

Analysis of the structures contrasting the thrusts

It is known that a composite plan church completed by a cupola in the central part is considered a highly pushing structure as it is shown by the comparison with other project previsions of the time after the Loreto experiences. The projects demonstrating this assertion are either P. Fugazza's little model of S. Siro Cathedral of Pavia with its external buttresses and the four corner towers, or the graphic plan for the new S. Petronio's in Bologna with inside partition walls between chapel and

chapel having the evident function of windbracing and with box-type structures and pillars in the four corner areas, that at Loreto are occupied by the towers. The drawing of S. Petronio's was made by B. Peruzzi, while the little model is by A. Arriguzzi (1515).

We have already dealt with the spurs and the rising above rafters when the barrel pointed vaults have been examined. Only one aspect of their function is to be pointed out: the different terminal subjects upon which the loads are discharged. To remove the thrusts, the spurs, that are true buttresses, when considered conjugated with the concave impost arch of the barrel vault, unload upon the four corner towers. The rafters lying upon the same plane containing the diagonal major arch of the cross vault below, with the function of flying buttresses, unload the thrusts on the intersection of the external facings of the Basilica, in correspondence of the towers, masonry angle characterized by a big moment of inertia. Remembering the nature of the ground in which the building was erected, the solution seems to be particularly remarkable.

We have already dealt with the vaults «a creste e vele» as a final element lacking any polar symmetry: they unload the thrusts of the series of vaults upon the external cylindrical surfaces creating every apse.

The materials

The walls, the vaults and the roof of the Basilica are all built with plain and shaped bricks for the cornices and the ribs, tiles and plain roofing tiles and also columns.

The Marche and the coast are made of clayey hills rich in waters that supply very good material for the manufacture of tiles. At Montorso, a hill between Loreto and the coast of the Adriatic sea, therefore very near the actual Basilica, there was a very active brick factory till the first years of the XX Century. On the contrary the region is almost totally without marble material, especially in the area around Loreto. This fact explains why the Basilica of the Holy House is all built with bricks linked with lime mortar.There are very few stone applications and all of them are in a type of limestone generally known as Pietra d'Istria, coming from Istria, or from Dalmatia, the actual Croatia. The reasons of this choice are either in its quality or in the easiness of the transports, since it is

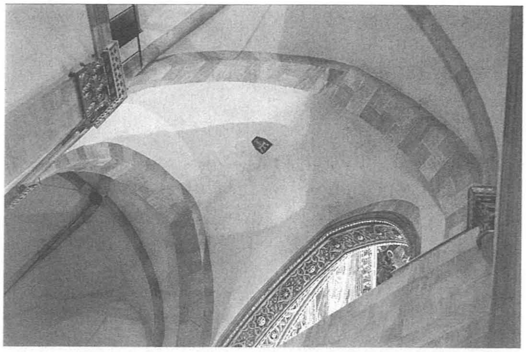

Figure 12
View of the barrel pointed vault

preferable to travel some more miles by sea than to walk for some kilometres less with carts pulled by oxen. The Istria stone puts together very good physical and mechanical characteristics and an exceptional endurance to the attack of the brackish air. Furthermore it is a remarkable experienced material, being not only the most used stone in Venice but also very common in the decorations of the Marche high-class palaces in the examined area. Therefore the material was known to the artisans who had to work it.

The Istria stone transported by sea was very cheap and easily to be supplied, being the quarries in a friendly territory under Venice, and easily to be embarked because they were very near the sea, coming from the Brazza island, the Veselje valley, or from the quarry near Pisino, called Orsera, today Kirmenjak or near Rovigno, nowadays Zlatni Rat. The coast near Loreto was rich in ports.

The wood used for the beams was imported, since in the Marche there were not forests that could supply the necessary square measure. Reading the Acts we understand that the purchase of the wood beams was a bigger problem than that of the stone.

For the presence of many rivers flowing from the Appenines there was a large availability of stone to produce lime and of lath to make mats.

The instruments used for the management of the yard

The use of instruments is not proved by archives sources, but by the practical necessity to realize what

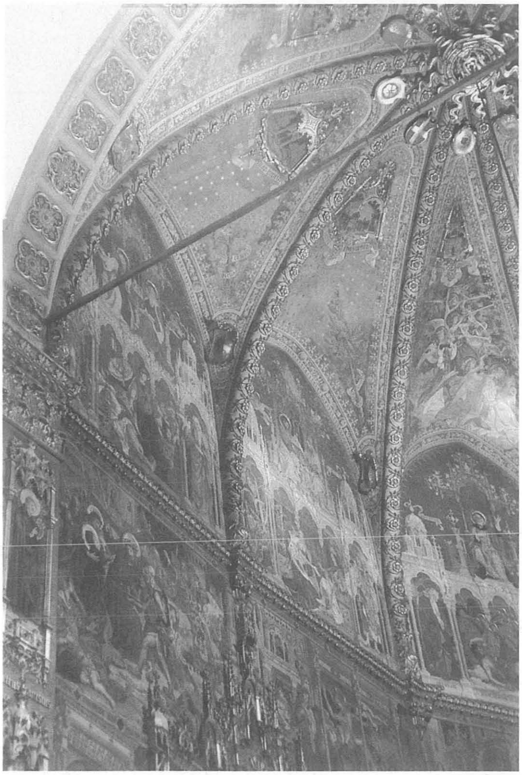

Figure 13
Detail of the intrados of a vault «a creste e vele»

was built.

The technicians erected a building containing the superior part already built of a hill, a new structure with the foundations on a three-dimensional ground. For these reasons they could not absolutely trace out the plan of the building judging the straightness of the surface by the eye and it was even less possible for them to realize a nearly approximate positioning in the centre of this plan of what existed without the instruments. The new building rose just to have the relic in the middle.

From here the necessity to resort to the geometrical quadrante and to the archipenzolo, also called square. The use of these instruments requested the presence in the yard of men with a very good knowledge of geometry. These instruments for the survey of the ground are described in the books of the time, such as the Treatises by Francesco di Giorgio, those by Mariano di Jacopo called Taccola and those by L.B.Alberti, even if their main application was for the best use of the new-born artillery. To be able to use practically these instruments,it was indispensable to have a tower in the area to be built.

From the examination of the structures the tower that may be considered pre-existent, or if not pre-existent however built, is the north-east tower. An indirect confirmation of this supposition about its use as a base for the measurements is the ascertainments of a constructive detail; the existence of a correction of the plan once arrived with the walls to a constant plane over all the perimeter that allowed to sight with a better accuracy as to the instruments. On this plane completely in view they made a correction of the dimensions proved by a step of varying width along the external perimeter. The north-east tower has zero error as to the base below confirming in this way to have been used as zero point of reference for the measurements.

NOTE

Tranlation into Englis by Anna Rosa Monelli

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The construction of fantasy. Ephemeral structures and urban celebrations in France during the eighteenth century

Eric Monin

In the eighteenth century, temporary constructions celebrating the most important events in the kingdom introduced both new urban ephemeral contexts and fictions with surprising atmospheres. This paper will first focus on the role of practitioners and workers involved in this process of creation. It will then study the properties of the construction materials of these ephemeral projects. At last it will consider practical issues related to the cost and the speed of construction, the safety and solidity of these inventive ephemeral buildings.

The Protagonists

Directors and craftsmen

The projects were co-ordinated by artists or architects who had previous experience with the construction of decorations for theatres and spectacles. Most of them were familiar with wooden frameworks and were also accomplished draughtsmen. For example, Jean-Nicolas Servandoni was one of the most famous *fête* designer in France in the middle of the eighteenth century illustrating the very strong technical relationships between the scenic art in theatres and ephemeral projects constructed in the most important cities in the kingdom.

It is noteworthy that Servandoni as well as Jean-Antoine Morand first began to work as a decorator at the theatre in the second part of the century. The latter had spent a few months studying with Servandoni to get experience about the making of scenic decorations and machines before he worked with Soufflot for the construction of the new theatre in Lyon. Morand also worked in Parma in the 1760's as a decorator for the theatre and he also designed ephemeral constructions for the celebration of the wedding of the future Ferdinando II with Maria Amalia, the archduchess of Austria. Morand was a fine frame designer. He knew a lot about carpentry as set as the projects he designed to celebrate the entrance of the king of Denmark in Lyon in 1768, the wooden tribunes he created in 1769 for *La Fête de Monsieur l'Intendant de Lyon*, and the amphitheatre he constructed in 1784 for the ascension of the aerostat the Flesselle. At the end of the nineteenth century, Morand was still famous in Lyon for the wooden bridge he built on the Rhone River.

In Nantes, before he became the architect of the classical theatre of the city, Mathurin Crucy also worked with one of his brothers as a festival designer when he decorated the square facing the old stock-exchange and the façade of this building to celebrate the birth of the Dauphin in 1781. Crucy also knew many things about wood frames because he began his career as a naval carpenter working with his father who controlled all the wood trade in the west part of France during this period.

Feast designers had to manage many things at the same time. In 1802, in the treatise he wrote about pyrotechnics, Claude Ruggieri insisted on the many

construction of a triumphal arch in Grenoble to celebrate the entrance of Monsieur le Maréchal et Monsieur et Madame La Marquise de Tonnerre. Even though this invoice did not take into account the paintings, the wooden ornaments cost more than twice the price of the whole wooden structure of the building. Moreover, the cost of the painted decoration covering such a construction accentuate the importance placed on appearance.

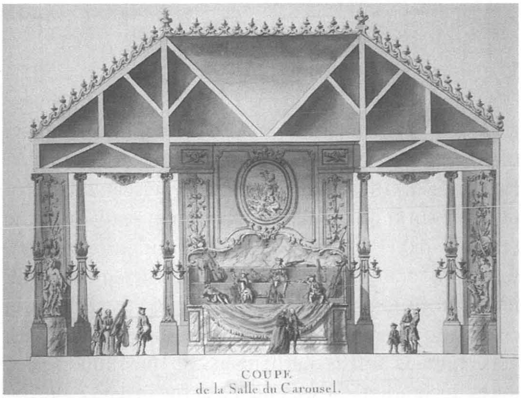

Figure 4
Fêtes publiques données par la Ville de Paris à l'occasion du Mariage de Monseigneur Le Dauphin les 23 et 26 Février M.D.CC.XLV. Cross section of the *Salle du Carrousel*

Classical Tools for Creation

When explaining the tools used to create ephemeral projects, fireworks displayers insisted on the function of preparation. Everything should be drawn before carpenters, painters and sculptors began their job. According to the treatise Casimir Siemienowicz wrote in 1651 about le *Grand art d'artillerie*, fireworks engineers had to make sure their projects were understandable thanks to the plans, elevations and sections drawn in preparation. Siemienowicz stresses this point by mentioning the basic principles of Vitruvius:

> D'abord que l'Ingénieur à feu aura conçu quelque belle pensée dans son esprit pour le dessein d'une machine pyrotechnique, il faut nécessairement qu'il la sache bien exprimer par ses idées, qui sont l'Ichnographie, l'Orthographie, & Scenographie : Et pour cet effet il est nécessaire scavoir un peu desseigner, ou tout au moins crayonner (comme dit Vitruve) afin qu'il puisse avec moins de difficultés coucher ses desseins sur le papier tracer les plans, lever ses profils, pour les pouvoir proposer nettement à ceux qui font la dépense des machines que l'on veut construire.[3]

General plans and perspective views were presented to the *Jurats* et *Echevins* before full size plans, cross sections, front views and details of the projects were given to the wood workers and painters to build the construction. In 1750, the Arnoult brothers and Tremblin prepared a large *fête* to celebrate the birth of the Duc de Bourgogne. When the celebration was cancelled because the birth was unexpectedly of a princess, the conductors of the event made an invoice to point out the drawings they had prepared so that they could be paid for their work. More than sixty drawings had been given to the Clerk's office of the city and to the workers involved in the construction of the decorations and ephemeral architectures: a map of the entire location of the celebration, plans and large drawings of the eleven buildings with all their ornaments, several cross sections and perspective views of the Temple which was planned on the Pont Royal, main elevations of the wooden frames and drawings of the triumphal arch that might have been located on the Pont Neuf, plans and an elevation of the framework of a great column and of a pyramid, plans, cross sections of grottos with a front view of their framework, details of ionic columns and many drawings of the boats planned to light the river where the celebration had to take place.

Sometimes, models made of wood, cardboard, wax or paper were made to survey the final appearance of the constructions. These models helped in the choice of the best solutions according to the function of the ephemeral buildings and they were also good tools for workers who could refer to them in case they needed more information about the final aspect of the constructions. Both Casimir Siemienowicz and Amédée-François Frézier insisted in their treatises on the role of models. They thought they were a very good way to emphasize and then correct the drawbacks of the projects:

> Ce ne sera pas assez d'avoir crayonné légerement sur un papier la forme de la fabrique qu'il desidera représenter, il sera bon aussi qu'il sache faire des modèles & prototypes de bois de cire, de plastre, de papier ou de linge collé ensemble, afin que par ce moyen tous les deffauts, inconvénient & deformitez puissent mieux paraître, & conséquemment estre corrigez avant que la machine soit bâtie.[4]

Concerning firework machines, Amédée-François Frézier noted that models could be used to chose the right locations to put fireworks and rockets to prevent the ruin of the whole construction during the display and to allow pyrotechnicians to reach safely all of these places:

> Il est même de plus convenable de faire en relief des modèles de ces édifices lorsqu'ils sont un peu composés, pour mieux prévoir l'arrangement des Artifices dans la situation la plus avantageuse, les moyens de les placer & d'y communiquer pour les faire jouer à propos, & prévenir les inconvénients qui pourraient arriver, si l'on manquait de ces commodités de communication, pour aller & venir où il sera nécessaire.[5]

The report prepared after the suspended celebration of 1750, tells us about the many models planned to help workers in their job. This document explains how the models gave information about the assembling of wood pieces, the location of the constructions in the site and the exact place of the fire-pots in the whole composition:

> Ce fut pendant cet intervale que les conducteurs de la fête continuèrent les modèles qu'ils avaient déjà commencés et les mirent en état de pouvoir servir à donner à chaque entrepreneur et surtout aux décorateurs l'intelligence de leurs ouvrages en leur mettant sous les yeux l'ensemble de toutes les parties qui devaient composer chaque édifice.
> Ces Modèles construits en bois, cire, carton et papier auraient été déposés dans les ateliers des Bernardins pendant le temps des travaux, et auraient servi encore à donner à chaque ouvrier des indications justes pour la pose de son ouvrage et surtout pour la disposition et les quantités de lumières.[6]

All these drawings and models prove that ephemeral projects were carefully designed before beginning the slightest construction. Drawings seem to be as important as in the field of architecture. Even though these projects were only ephemeral ones, this process shows the serious nature of such events.

The Materials

The study of the materials used to build these ephemeral constructions raises three major kinds of questions. First it was necessary to develop a global approach concerning the cost and the speed of the process of construction. Money and time did represent the most important criteria of this process of construction. Second, we have to study the connections between ephemeral proposals and permanent architecture. This point orientates the choices creators make to produce illusion. Third and last, festival designers had to consider safety and therefore the solidity of the projects they propose.

Cost and speed of construction

One of the most important challenges of such projects was to transform urban sites without disturbing the city's daily organization. It was impossible to block off a street and temporarily stop the circulation of carriages and people in a part of the city. Everything had to go on inside the city without any trouble. This supposed the projects had to be assembled very quickly, sometimes only few hours before the event starts. So, ephemeral structures had to be prefabricated, tested and proved before they were erected on their final location. This meant carpenters and other workers had special work sites, large enough to prepare the whole projects.

Secondly, although they temporarily changed the townscapes of the main cities of the country, these constructions were not intended to make durable marks that might disturb the existing shape of their location. Many invoices describe how wooden frames had to be strongly fixed in the ground of the places where they were located. This was unfortunately damaging the ground of the urban public space and hampered the circulation of carriages. In order to avoid the multiplication of holes in the main squares of the city, Jacques-François Blondel formulated the solution by proposing durable foundations where the fireworks machines could be installed without causing any trouble in the site:

> D'ailleurs pour éviter toute dépense accessoire & de préparation, ne pourrait-on pas établir à demeure, des fondations sous l'aire du pavé pour les Fêtes terrestres, préparer & conserver des équipages pour celles qui se donneraient sur l'eau ; de manière qu'il ne s'agit plus que d'en confier le posage à des inspecteurs intelligents, qui pourraient en presser l'exécution au gré du Prince ou du Magistrat.[7]

In the *Plan Général du cours de la rivière de Seine et de ses abords dans Paris* Moreaux published in 1769, the author proposed something quite similar. In his embellishment project for the *Place de Grève* Moreaux planned a special area for the location of the fireworks machines. This spot was located along the river so that thousands of people could have attended to the fireworks displays from both banks of the river. It is no coincidence that when he prepared the celebration of the birth of the Dauphin in 1782, Moreaux decided to locate the huge fireworks machine on this location according to his previous plan.

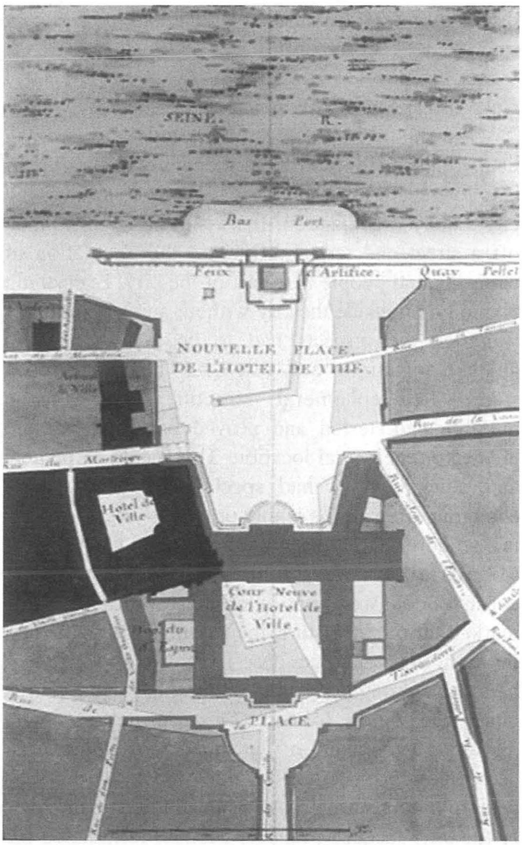

Figure 5
Plan d'aménagement des berges de la Seine de Pierre-Louis Moreau (1769). Agrandissement de l'Hôtel de ville

In the chapter he devoted to «les Edifices Elevés en Charpente à l'occasion des Fêtes publiques» (framework constructions for public celebrations), Jacques-François Blondel also insisted on the notion of modularity. It seemed very important to him to use modular construction so that basic elements could be used and reused for many projects, thereby avoiding waste. He would not tolerate temporarily buildings were so expensive because of their totally extravagent designs. The solution Blondel suggested was to keep money thanks to the creation of a good modular system of construction that may have supply any imaginative project :

> Pourquoi ne se prémunirait-on pas de magasins pourvus de hangards & d'ateliers où se prépareraient & se façonneraient d'avance ces sortes de décorations ? Pourquoi les Chefs de ces entreprises d'éclat n'occuperaient-ils pas leur plaisir à préparer différents objets de ce genre ? Pourquoi ne pas conserver une certaine quantité de corps d'Architecture, toujours préparés, mais composés partie par partie, d'après un ensemble général & une dimension relative au lieu où devrait se passer la scène, soit sur l'eau, soit sur la terre, de manière qu'il devienne possible, à l'occasion d'un événement imprévu, d'élever en très peu de temps, telle ou telle sorte d'édifice qu'il conviendrait ?[8]

Although Jacques-François Blondel did insist on this point, ephemeral constructions were quite often stored as best as possible to be reused later for other projects for economic and temporal reasons. Decorations were carefully taken down the day after the celebration and placed in municipal sheds. Invoices prove how old decorations were repaired and adapted to the subject of new events as they were often unpacked many years after their creation. The decorations used to celebrate military victories generally represented soldiers fighting near a city gate. Although the topic of the celebration was quite similar between two victories, it was necessary to adapt the decorations to their geographic context as much as possible. In 1758, the decorations and

firework machines constructed to celebrate the military victory on *les hessois et les hanovriens*, were the same used a few months before for the victory of Hartembeck. Ornaments were quickly renewed with painting:

> 1. Sera fait le changement de disposition à toutes les masses de rochers au pourtour et seront peints les châssis de trois pieds de haut sur cent quarante quatre pieds de pourtour par le bas pour les trois faces principales.
> 2. Seront retouchés les quatre parcs occupés et peints en pierre, et ces panneaux seront retracés et faits en pierres.[9]

Architects sometimes made small changes to adapt old decorations to new projects. This example is quite clear when the architect also asked to get back six figures formerly painted to celebrate the victory of Port Mahon:

> 8. Seront repeintes en marbre blanc avec leurs attributs et socles en rochers, de six pieds de large sur quatre pieds de haut, les six figures qui ont servi au feu des réjouissances qui ont été faites à l'occasion de la prise de Port Mahon.[10]

Wooden decorations placed against the façades to support illuminations were also reused several times even thought they were not always located on the same buildings. As our electric Christmas fairy lights, these elements could be adapted to different façades to make them temporarily more regular with the symmetry of geometric patterns traced at night by hundreds of fire pots. In Paris, the buildings of the Echevins were usually emphasised during public celebrations as follows:

Figure 6
The same decoration was used to ornate the houses of M. Mirey and M. Frenaye in 1751 and 1752

— The lighted portico designed for the façade of the house of M. Mirey in 1751 and in August 1752 to celebrate the birth of a prince and the recovery of the Dauphin was reused in September 1753 to celebrate the birth of the Duc d'Aquitaine and placed on to the façade of the Hôtel of M. de la Frenaye to make it more regular and symmetrical.
— The lighted ceremonial door located on the first floor of the house of M. Gilet in 1751 was exactly transferred to the house of M. Caron in 1753 without any change, because of the identical width of the two houses.

Figure 7
The same decoration was used to ornate the houses of M. Gilet and M. Caron in 1751 and 1753

Sometimes, to make the whole celebration a little bit less expensive, municipalities only paid for the materials used to produce the decorations, and carpenters could recever them after the event in lieu of wages. According to a prior contract, the amphitheatre constructed in Lyon in 1784 by Jean-Antoine Morand to attend to the taking off of the

aerostat *Le Flesselle*, belonged to the carpenter who constructed it, only one month after it was built.[11] It was clearly stipulated that in case the festival continued after this date, the municipality would have rent the whole construction from its new owner. This kind of contract did make the events less expensive and it was a new way to tackle the problem of the price of these ephemeral celebrations. This process allowed cities to keep money by renting ephemeral decorations only when needed or by asking private directors to manage the organisation of the whole event. People who were interested in attending the events had to pay for their seat several days prior, so that the event could take place thanks to the money previously collected. Unfortunately, we must note that such subscriptions did transform public celebrations into private spectacles. In Nantes, during the second part of the eighteenth century, Le Seur was the promoter of several festivities organised on the *place de la Bourse*. The same decorations were reused many times to ornate the square. Le Seur was used to organising public subscriptions before the events. In 1764, he organised a last festival and then sold all the different decorations as mentioned in the advertisement for the event. This may prove how it was difficult to manage successfully this kind of entertainment.

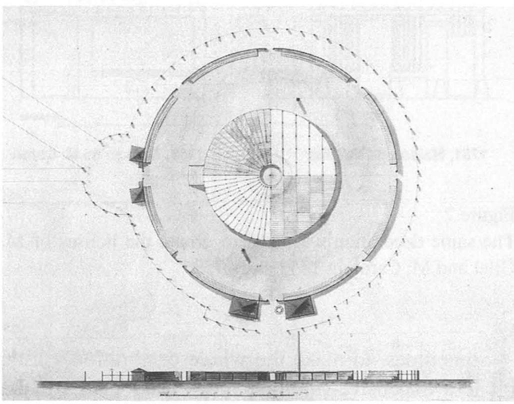

Figure 8
The ascension of the aerostat *le Flesselle*, january 19th, 1784. *Plan de l'estrade (laissant voir la construction de la charpente), de l'enceinte, avec les mâts. Au pied, coupe générale*. Archives Municipales de Lyon, 3.SMO.399

Residents were usually allowed to build tribunes in front of their houses in order to make money by renting seats to spectators. These constructions participated in the planning of the festival area. Carpenters were also allowed to erect tribunes all around the spots of public celebrations. This was a way to increase their wages and give them an incentive to build. When he proposed a magnificent project to celebrate the entrance of the Spanish Infant in Bordeaux in 1744, Jean-Nicolas Servandoni insisted that it would be necessary to thank carpenters for their work, by allowing them to build tribunes all around the royal square. This process also shows how municipalities successfully assigned to private directors the task of managing a part of these celebrations.

According to the process of creation of public celebration, thrift and speed of construction are closely linked principles. In his *Cours d'architecture,* Jacques-François Blondel does consider both of these notions at the same time. These principles also seem to orientate the very aesthetic dimension of the ephemeral projects. Blondel proposed to compensate for the lack of invention that might result from the use of prefabricated standard modules, by adding moulded cardboard sculptures following to the theme of the celebration. Ultimately, the beauty of the project came from its convenience of execution and from its ability to resemble permanent architecture. This last effect mainly depended on the work of painters who had to make illusion thanks to their watercolours:

> Pourquoi ces mêmes magasins ne contiendraient-ils pas aussi un certain nombre d'accessoires, tels que des armoiries, des devises, des bas-reliefs, des statues, des trophées moulés en cartonnage, qui serviraient à symboliser ces différentes décorations, lesquelles pourraient, selon l'occasion, se composer ou se décomposer dans leurs dimensions. La Peinture à son tour déploierait toutes ses ressources pour les imprimer en pierre, en marbre, y appliquer l'or ou l'azur : ressources peu dispendieuses qui embellirait ou simplifierait l'ordonnance de ces monuments.[12]

Imitation

Ephemeral constructions had to look like permanent ones. In this way, the *fête* designers created the illusion of unexpected worlds and phantasmagorias.

The *Encyclopédie résonnée des sciences, des arts et des métiers* defines of this idea, in other words *l'architecture feinte*:

> ... [on appelle architecture feinte] celle qui a pour objet de représenter tous les plans, saillies & reliefs d'une architecture réelle par le seul recours du coloris ... (...) ... celle qui concerne les décorations des théâtres ou des arcs de triomphe peintes sur toiles ou sur bois, géométralement ou en perspective, à l'occasion des entrées ou fêtes publiques, ou bien pour les pompes funèbres, feux d'artifices, &c.[13]

Ephemeral constructions were a kind of *architectures feintes*. The only way to make them similar to durable architecture was through the use of colour as mentioned in this definition. Before the structure, everything was based on imitation of true construction materials especially stone. The challenge was to simulate stability with paper, canvases, cardboard and of course painting. Jean-Nicolas Servandoni knew the secret recipes to attain this goal as for instance in 1739, when he designed a *Temple de l'Hymen* on the far west side of the *Ile de la Cité* in Paris, to celebrate the wedding of *Madame Première* with the Infant Dom Philippe. Apart the brilliant composition of the façade of the building, he advised to use paint simulating the colour of stone:

> L'on avait emprunté de la peinture qu'une couleur de pierre générale & uniforme, dont on avait recouvert toutes les matières qui avaient été employées pour la construction de cet Edifice.[14]

Five years later, he wrote a similar sentence to describe the painting that decorated the magnificent hall and triumphal arch he built in Bordeaux for the entrance of the *Dauphine*, managing to associate a perfect coherence between the shape and the appearance of the construction:

> Tout le Bâtiment est en relief composé dans la sévérité des règles, il est aussi bien construit et imite si parfaitement la pierre qu'hors de le toucher, l'on s'y trompe par la seule apparence.[15]

The success of these projects also depended on the illusion of abundance and luxury they created. Ephemeral wine fountains imitated water fountains made of marble, with bases and columns often painted in gold to accentuate the value of the whole construction. Colours and figures covering ephemeral construction were chosen to resemble famous buildings, such as with the colonnade designed for the Pont Neuf in Paris to celebrate the first wedding of the Dauphin in 1745. The painting of the ceiling of this wooden ephemeral construction was directly inspired by the colonnade of the Louvre located just nearby the spot of the fête:

> Le plafond de la gallerie dans toute sa longueur aurait été peint dan le goût de celuy de la colonade du Louvre qui regarde St Germain lauxeroix.[16]

Even fantasy, however, was guided by the rules of classicism. *Fête* designers attempted to follow

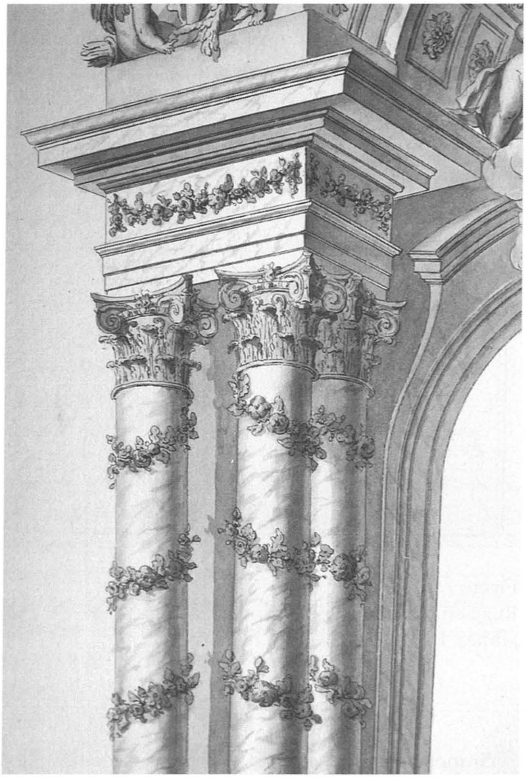

Figure 9
Detail of the façade of the *salle de la place Dauphine*, in *Fêtes Publiques données par la ville de Paris, à l'occasion du mariage de Monseigneur le Dauphin, les 23 et 26 février 1745*

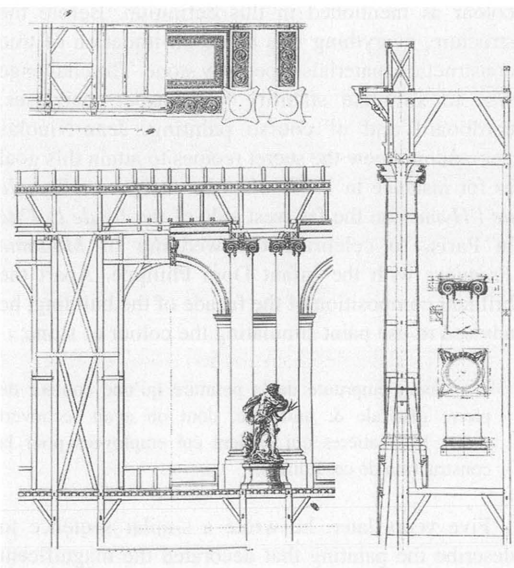

Figure 10
Gallery designed to celebrate the first wedding of the Dauphin in 1745. Elevation showing the structure with its ornaments and a view of the painted ceiling. Archives Nationales, K 1008, n°5. Section. Archives Nationales, K 1008, n° 4 bis

classical rules of composition to build their constructions according to *Convenance* (suitability and regularity). The hall Servandoni created in Bordeaux in 1745 did strictly respect the principles of classical architecture:

> Ce bâtiment était composé dans la plus grande sévérité des règles selon les anciens, les colonnes, leurs bases, chapiteaux, entablement, fronton, bas relief et ornements étaient totalement de relief...[17]

The connection between durable and ephemeral architecture could also be found in treatises on pyrotechnics which began to take account of architectural aesthetic restraints. Fascinating palaces, triumphal arches or small ancient temples were the main architectural themes developed for eighteenth-century festivities. Jacques-François Blondel suggested that ephemeral constructions should be embellished by using the five canonical Orders. As regards the aesthetic rules for classical architecture related to the orders determined by Vitruvius, Casimir Siemienowicz tried to apply the same criteria to his ephemeral constructions. This shows how even these temporary constructions had to be coherent and harmonious according to standard architectural practice. From Casimir Siemienowicz to Claude Ruggieri the five architectural Orders prevailed, even when considering pyrotechnic machines or decorations. In his treatise, Ruggieri devoted a chapter to «Les Règles d'Architecture pour l'Artifice» (architectural rules for fireworks displays).

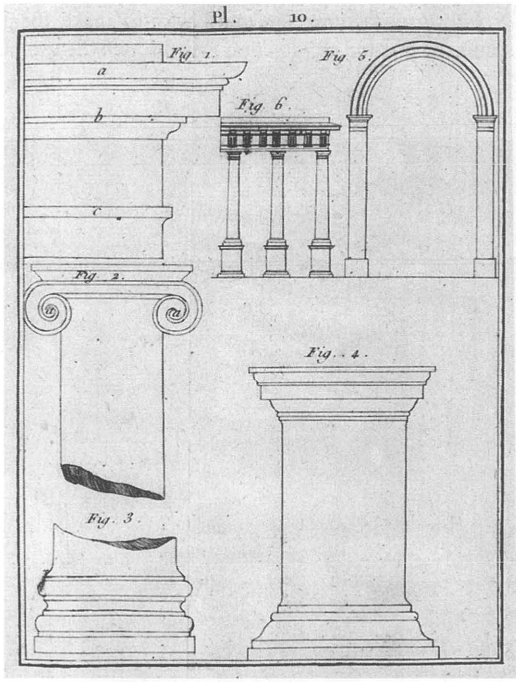

Figure 11
Ruggieri (Claude), *élémens de pyrotechnie divisés en cinq parties*, Paris, 1802. Planche 10

Sometimes, ephemeral proposals could also influence durable architecture because of the quality of their intrinsic composition. The drawing of the temple Servandoni designed in 1739 was mentioned a few years later in the compilation of analytic architectures published by Neufforge at the end of the

1750's. At the same time, Jacques-François Blondel encouraged his students to draw some fireworks machines as a way to train themselves in the composition of various architectural styles.[18]

Safety and Solidity

In his treatise on pyrotechnics, Amédée-François Frézier also dwelt on public safety by insisting that all materials used for the construction of urban decorations be fireproof or fire-resistant. This cautious step to avoid the risk of fire was a novel consideration. For example, Amédée-François Frézier noted that it was safer to use watercolors instead of oil paint for the scenery and decorations covering large boards or canvasses stretched on the wooden ephemeral structures. The effectiveness of this admonition is suggested by the rapidity with which it was adopted, for subsequent invoices repeatedly specify watercolors.

Although these ephemeral structures were only decorative, architects had to build them solidly enough so that they would not fall on people. According to the Vitruvian principle the ephemeral constructions had to last long enough for these short-lived celebrations. However, it was not possible to predict the exact level of solidity these projects should have, because of unpredictable weather conditions. As Amédée-François Frézier and Claude Ruggieri suggested, the safest way to tackle the problem was to follow the technical know-how of construction. To check the strength of the projects, special commissions were called as for instance in the two following examples:

— Firstly, to celebrate the birth of the «Dauphin» in 1729, the Spanish Ambassadors in Paris ordered a great ephemeral hall to be located next to the Hôtel de Bouillon. A big storm caused the first construction to collapse. A new structure was erected and closely inspected when completed. The commission was led by Robert de Cotte, first Royal architect, and even the chief of the Royal Police in Paris was a member of the commission, as mentioned in the text Le Chevalier Daudet published in 1731.
— Secondly, at that time most of the Parisian celebrations took place on the *place de Grève*, in front of the Town Hall. The tribunes set up by the residents in front of their houses were thoroughly verified by no less than a dozen officials, such as bailiffs, aldermen, the Attorney General and his men, and finally the architect in charge of the safety report. The

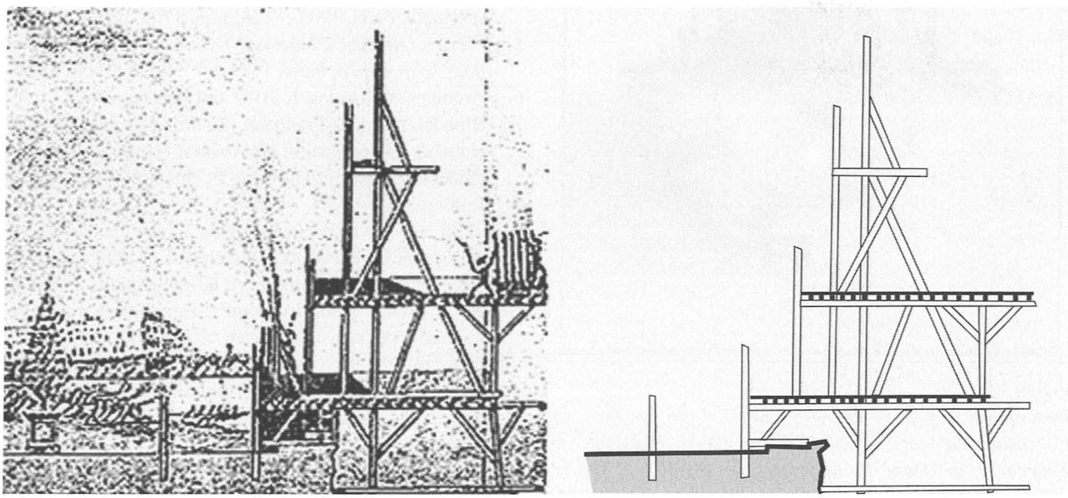

Figure 12
Feu d'artifice en Grève, pour la naissance du Dauphin, BHVP. Detail and constructive principle

commission controlled the arrangement of the wood pieces and how they were put together so people could properly sit on the tribunes. They also made sure they were built in accordance with the previous submitted outlines.

A whole process of construction

To conclude, it is noteworthy that the various aspects we mentioned in this paper all contributed to the definition of a very specific field of production. Artists, architects and workers involved in this process of creation were trying to make fantasy thanks to the clever use and assemblage of the most basic materials of construction.

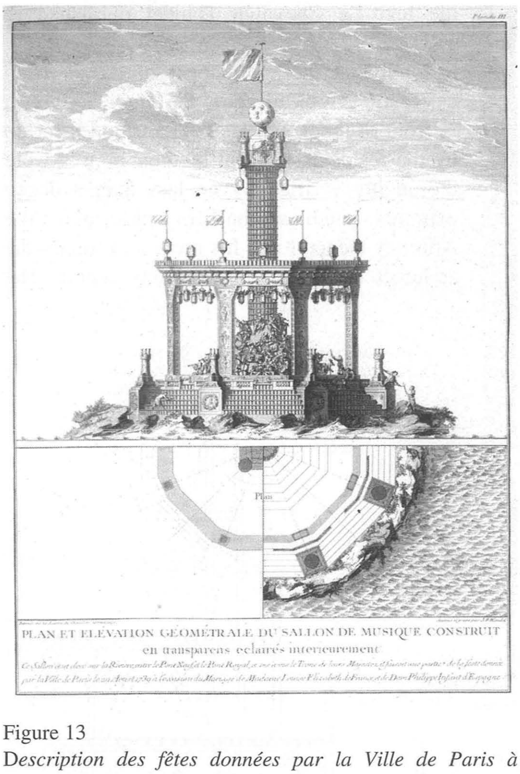

Figure 13
Description des fêtes données par la Ville de Paris à l'occasion du mariage de Madame Louise-Elisabeth de France et de Dom Philippe, Infant & Grand Amiral d'Espagne, les 29 et 30 août 1739, Paris, Mercier, 1740. Planche III, «Plan et élévation du salon de musique...». Cl. Ch. Hémon, Musée Dobrée, Nantes

The success of these projects depended on the way designers managed to control the events according to the many constraints of the chosen sites. The surprising shapes of the projects and the new townscapes or lightscapes they set up in the city allowed many experiments and could also introduce innovations in the field of architecture. By answering questions of location, construction, safety and solidity, festival designers managed to transform daily common places into unexpected fictions where people could temporarily imagine they became the main actors of a phantasmagoria.

Notes

1. Ruggieri (Claude), élémens de pyrotechnie divisés en cinq parties, Paris, 1802, p.xij.
2. Frézier (Amédée-François), *Traité des feux d'artifice pour le spectacle*, Paris, 1747, 1ère édition, 1706, p.IX.
3. Siemienowicz (Casimir), *Grand art d'artillerie*, mise de latin en français, par Pierre Noiset. 1651, p.381.
4. Ibid. In his treatise, Frézier devoted some lines to the same topic: «Il faut former le dessein d'un Théâtre qui convienne au sujet de la réjouissance dont il s'agit, comme nous avons dit cy-devant, de chacun de ces Sujets en particulier. Il faut coucher ce dessein sur du papier pour en voir l'effet, ou ce qui est encore mieux, pour en prévoir les inconveniens, en dresser un petit modele de bois ou de carton collé», in Frézier, (Amédée-François), *Traité des feux d'artifice pour le spectacle*, Paris, 1747, 1ère édition, 1706, p.364.
5. Frézier (Amédée-François), *Traité des feux d'artifice pour le spectacle*, Paris, 1747, 1ère édition, 1706, p.450.
6. Archives Nationales, K 1010, n°1154. pp. 27–28.
7. Blondel (Jacques-François), *Cours d'architecture ou traité de la décoration, distribution et construction des bâtiments*, Paris, 1771. Tome II, chapitre VII, p.276.
8. Ibid., p.274
9. «Etat des ouvrages de peinture à faire de l'ordre de Messieurs les Prévôt des Marchands et Echevins de la Ville de Paris pour faire servir les décorations du feu de la fête donnée pour la Victoire d'Hartembeck à celle du feu qui doit être tiré devant l'Hôtel de Ville, le 28 Octobre 1758, pour la Victoire remportée sur les hessois et les hanovriens, les dites peintures faites par le Sr. Dumesnil, Peintre ordinaire de la Ville». Archives nationales, K 1013, n°245[1].
10. Ibid.
11. «Devis du charpentier Joseph Guillet, afin d'ériger l'enceinte en bois de sapin destinée à accueillir la célébration du lancement du Flesselles». Archives

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16. Archives Nationales, H/2/1861
17. Op. cit. note 14.
18. Op. cit. note 7, p. 278.

Search of a method to analyze a technological-constructive aspect in historical genoese villa: The wooden structure of the roof

R. Morbiducci

Many suburban villa of remarkable architectonic and technological interest were built from the 15th to the 18th century in Liguria, a region of Italy, and in particular in areas closed to the Genoa city (see Figure 1). These villa were built by the most important families as vacation home. This trend to build new villa was due to an economic boom that contributed to develop one of more important architectonic periods of the city.

The studies of these historical villa are numerous (i.e. Galliani 1984, Marchi 1987) both within the architectonic history and within the building technologies. In the present paper a particular technological-constructive aspect is analyzed, the

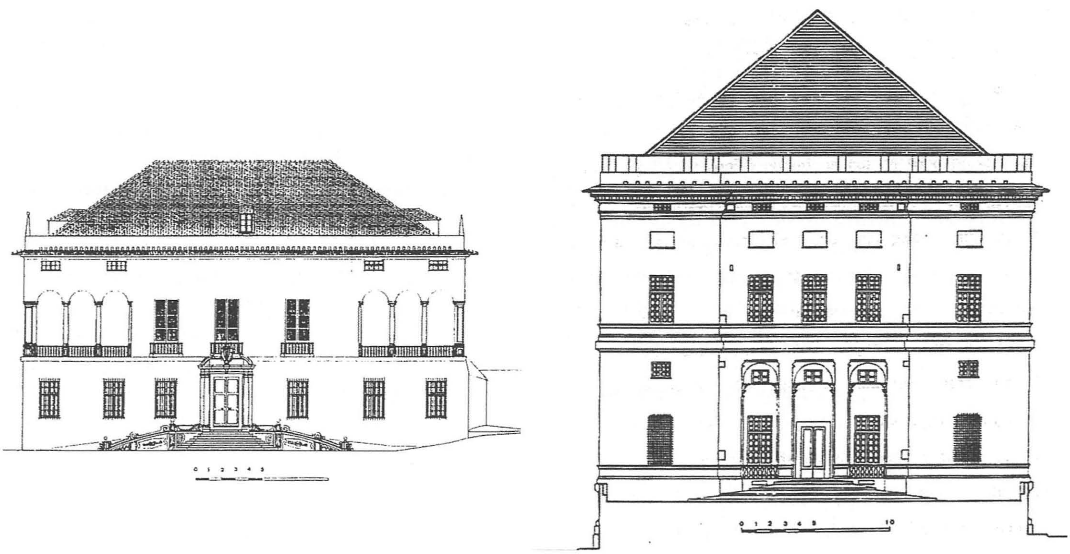

Figure 1a and 1b
Examples of historical Genoese villa: (a) *pre-alessiana* villa (Musso-Piantelli villa); (b) *alessiana* villa (Grimaldi villa)

wooden structure of the roof. The Genoese villa are named the *pre-alessiana* villa and *alessiana* villa. Alessi was the architect that developed a particular architectonic style applied also for these vacation homes during the 16th century (see b). The villa built before present a different style (see a).

A first superficial analysis of the villa roofs do not recognize a common constructive logic, because it seems that a precise framework do not exist. A more detailed study consents to individuate an uncommon constructive logic of pre-industrial builders that could be influenced by the naval technology. In fact a three-dimensional structural scheme due to the work of expert craftsmen and careful builders can be observed. These builders were able to build large structures, where every structural element played a precise role.

The use of the tridimensional structure of the Genoese roof was due to various reasons. For instance, the architectonic-functional organization of the villa in which the first floor large hall requested a large zone without supports and thus also in the roof structure requested uncommon technological solutions; the requirement of magnificence by the customer that implied darling architectonic solutions for the villa and for its roof; the local climate with the strong wind and the strong slope of the roof that suggested to use techniques and logic of tridimensional ship construction.

Three different analyses were made to verify and to make out a precise constructive technique in the wooden roofs. An *historical analysis* was conducted to compare the indications within many record office documents (in particular within several old tenders) to the direct observations made during investigations on the spot and to the results of the structural analysis. Several rules to build a new construction were individuated in the historical documents. Furthermore this analysis shown that these large structures were the result of many different competencies, for instance the knowledge of the wood tillage technique, the ability to select good materials, the presence of expert craftsmen trained in the shipyard. A *technological analysis* was conducted to study the materials, the techniques used to built the wood structures, the structural scheme planed and every useful elements to understand the roof system. Finally a *structural analysis* was conducted to individuate, if it existed, a common constructive logic for the roof and to plain a specific method to study this kind of structure. For this aim several roof of Genoese villa were studied, three rectangular and three square. Several structural models were developed to make finite element analyses to verify the global and local equilibrium in different load conditions and varying some boundary conditions.

HISTORICAL ANALYSIS

Genoa was a important maritime city with a long shipyard tradition. For this reason a large knowledge about the timbers for constructions and their tillage were acquired and an expert craftsmen worked in the city. An interesting element of the developed technological-structural knowledge was the mutual influence between the shipyard and civil yard that characterized every phase of wood use, from the tillage to the construction of wood structures.

In the 16th and 17th century the Liguria was a region with large wood lands. Several kind of woods were present in these lands, i.e. chestnut wood, oak wood, beech wood, fir wood. These timbers were used to build both buildings and ships. The seconds were essential for the maritime trading of the Genoese Republic that managed also the phase of transfer of the timber. The timber was of three different types, *line* timber, *curved* timber and *forked* timber. The first were used to produce long beams (i.e. for large floors and roof framework), planking and masts. The others two types were obtained shaping the trees during the growth and they were essential for the shipyard, but they were useful also for roof parts.

In the shipyard a rigid work organization was in force with division of competencies in the different constructive phases. The person in charge of the construction was the *magister caput operis*, he had to provide the provisioning of timbers from the wood, to list and control the timbers in the storehouse. The *magister caput operis* had the global technical responsibility of the shipyard, while the *work chief* was the designer that designed the hulls and the single components, went to the wood to select the timbers and took on the workers. Other persons had specific tasks in the shipyard, for instance the *axe master* had an important task in the hull construction. Generally the workers came out of Genoa and the work was differently distributed during the year, thus the

workers worked in different yards and with different tasks for construction of ships and buildings. This is one of the reason of the mutual influence through the shipyard and civil yard.

Since the availability of good timbers was scarce the good wood element from the demolition of old ships or buildings were utilized again in new constructions. For instance masts, spars were retrieved from old ships, because these elements did not submit to putrefaction due to continue contact with water; other wood elements were retrieved from floors and roofs of old buildings. The retrieved wood elements were indifferently used again in shipyard or civil yard

Several structural aspects evidence that mutual influence, for instance to the use of a wood planking that characterized the light Genoese galley and the large roof of the Genoese villa. Furthermore the wood planking and slabs of slate for the final layers of the roof are a peculiar characteristic of the monumental Genoese roof of historical villa. Another common element in the construction of ship and roof is the great use of nails in the joints and in the planking.

Besides the previous general information traceable in literature (i.e. Montagni 1993), the construction of the roof was one of more described part in the old tenders. For this reason these documents were read to find information about the phases of roof construction and to individuate a common constructive logic. The dimensions of structural elements, the differentiated use of woods and the presence of recurrent terms were found. Often the documents were not relative to existing or visible constructions, but a standardization of the tender was found, in particular about the dimensions of the structural elements that were verified also during the investigations on the spot made for this work in different villa.

In the documents many specific information about adopted solutions were found: the ratio through the greatest high of the roof and its base (5/12) (that is a slope between 30° and 45°); the choice of different timbers for different structural elements; the different

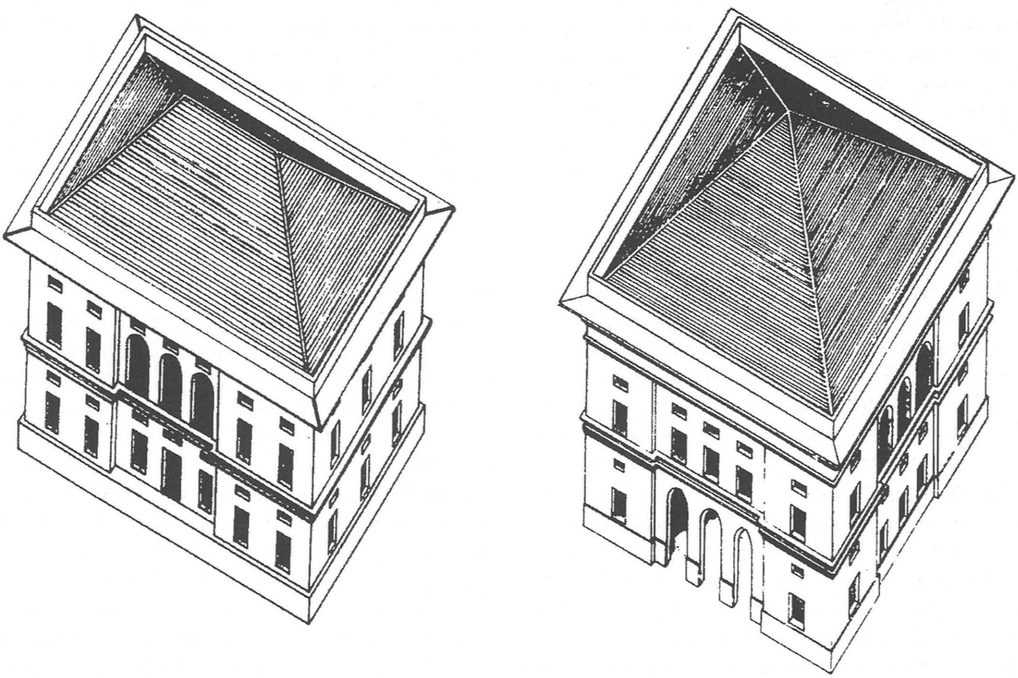

Figure 2a and 2b
The two principal kinds of roof of Genoese villa

shape and dimension of the structural elements; how to place the different parts of the structure with particular attention for joints through the elements; the shape and dimension of iron parts to fixed the walls with the roof structure; where and how to use the nails to connect the structural elements; how to place the slabs of slate (laid on third in the two directions) for the final layer of the roof; the projection of the eaves bound projection (500–625 mm); the characteristics of the structure to pick the rain water; etc. (for more details see Macor et al., 1993).

TECHNOLOGICAL ANALYSIS

The develop of pre-industrial building culture is strongly linked to the empiric knowledge acquired during a long time, besides in the pre-industrial age there was a conjunction through the design and executive phases. Thus a technological-constructive study is useful to analyze different constructive aspects of this kind of structure. The different part of structure were analyzed, the main structure, the secondary structure, the rooftop and the joints.

The roof of Genoese villa is certainly one of most representative elements of the urban skyline for its shape, strongly leaning, and for its black-gray color due to the slate slabs. It can be a hipped roof or a pyramidal roof (see Figure 2), with a slope between 30° and 45°.

The structural solution used for the roofs is original (see Figure 3), the roof has a tridimensional behavior. The *main structure* do not use the traditional truss, but it is constituted by rings of horizontal large continue beams (circular shape; diameter: 200–300 mm; length: 5–15 m; larch wood or fir wood) on different kinds of wood supports (circular shape (diameter: 120–200 mm), roughly square (side: 120–140 mm) or quarter part of a circle in shape; length: 2–6 m; larch wood, fir wood or chestnut wood). Besides the bearing walls (see Figure 4), characterizing the villa plan, are prolonged like direct supports of the *main structure* or like indirect supports by means of wood shores. The planimetric order of the walls is restrained by some schemes. In particular they are disposed on a quadruple cross partition for square villa, while they coincide with the walls of the main hall of first floor for the rectangular villa. These walls are in stone masonry.

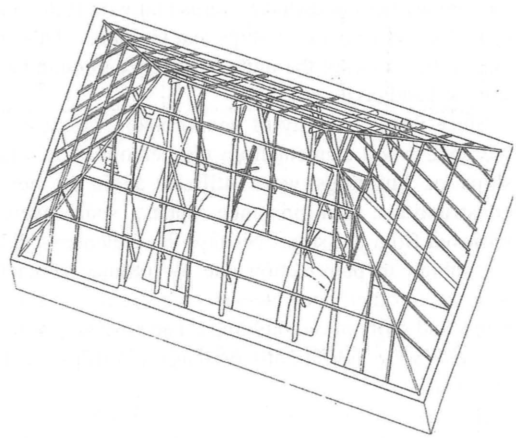

Figure 3
An example of the roof structure (Musso-Piantelli villa)

The *secondary structure* is constituted by the rafters and by the wood planking. The rafters rest on the main beams and form a thick framework with a step of 250 mm. Generally they are in chestnut wood with a section almost rectangular (on the average 70 × 90 mm). The wood planking (width 200–250 mm, thickness 20 mm), also it is in chestnut wood, is nailed to the rafters. The planks are completely placed side by side like the planking of a ship. Furthermore the planking of a traditional roof decays and so it has not a structural role, while in the Genoese roof it is also protected by the slate rooftop. For these characteristics its structural role is verified in the present work.

The *rooftop* is constituted by slate square slabs (dimensions 570 × 570 mm, thickness 4–8 mm) setting parallel to the boundary of the roof. The *rooftop* of Genoese roof has many characteristic details, but for the present study it is important to underline the technological details that improve the structural strength of the roof. The slabs are laid on they self to have a triple overlay and they are fixed to the planks by nails and mortar. The mortar seals the slabs also when it rains with a strong wind and increases the connection with the secondary structure.

The different elements of the roof structure are jointed to warrant the structural safety. The genoese carpentry used a local technique for the *joints* simpler that the traditional historical technique and with a

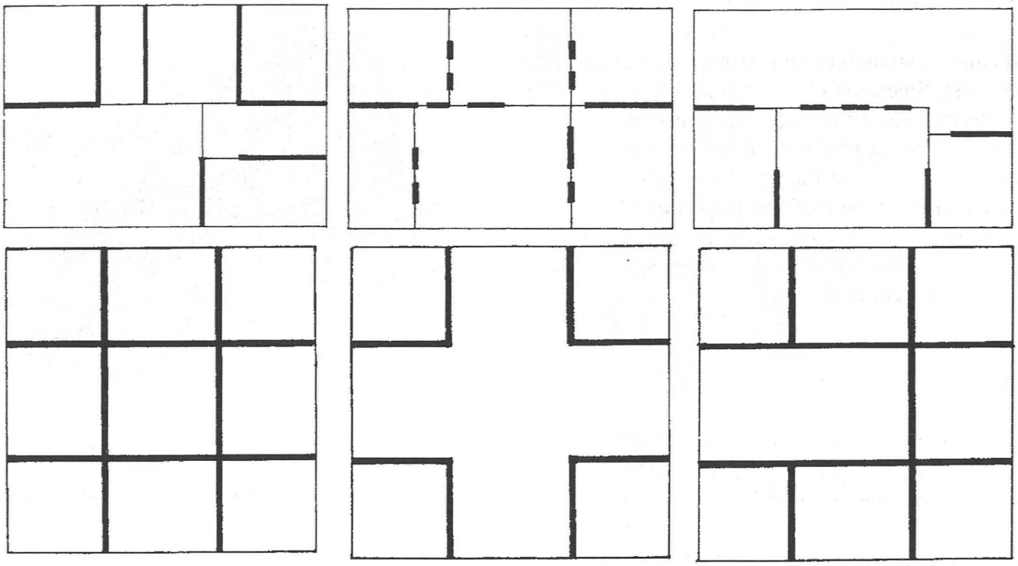

Figure 4
The disposition of the bearing walls like supports of the roof structure

large use of nails. Since the main structural elements, like the horizontal beams, have large dimensions and are just rough-hewn, keeping the circular section of trunk or carrying out a rough squaring, their relative joints assume a deceptive modest aspect, while they are structurally very effective and they are systematically used to solve the same constructive problems in different villa; sometimes careful realizations of joints were observed, for instance in some villa large horizontal beams are connected by perfect supports in the corners (see a,b); in the other cases the joints are rougher, but very effective, in which the structural role of different elements are correctly understood (i.e. c,d).

STRUCTURAL ANALYSIS

The structural analysis was conducted to individuate, if it existed, a common constructive logic for the roof structures and to plain a specific methodology to study this kind of structure. For this aim several roof structures were studied, three rectangular and three square. In particular several structural models were made and applied to finite element analyses to verify the global and local equilibrium in different load conditions and varying some boundary conditions. A commercial code was used for the finite element analyses (Ansys 1999).

The roofs were directly examined, that is every roof was surveyed analyzing in detail the technological-constructive solutions. Then the recorded information were used both to build the numerical model and to individuate the technological-structural scheme of the historical builders, in order to explain the past work in present day terms.

In the following the main information used to create the numerical model are summarized: position and dimensions of perimetral and secondary walls; type of timber, position, and dimensions of main structural wood elements, of every kind of wood supports, of rafters, of planking and of rooftop; analysis of joints, that is their shape, shape and position of nail, connection type (simple overlap, perfect joint, etc.).

The analyses were conducted with the hypothesis of intact carpentry, knowing that this hypothesis did not consider the real decay of the roof structures. This assumption is due to the aim of the present work, that

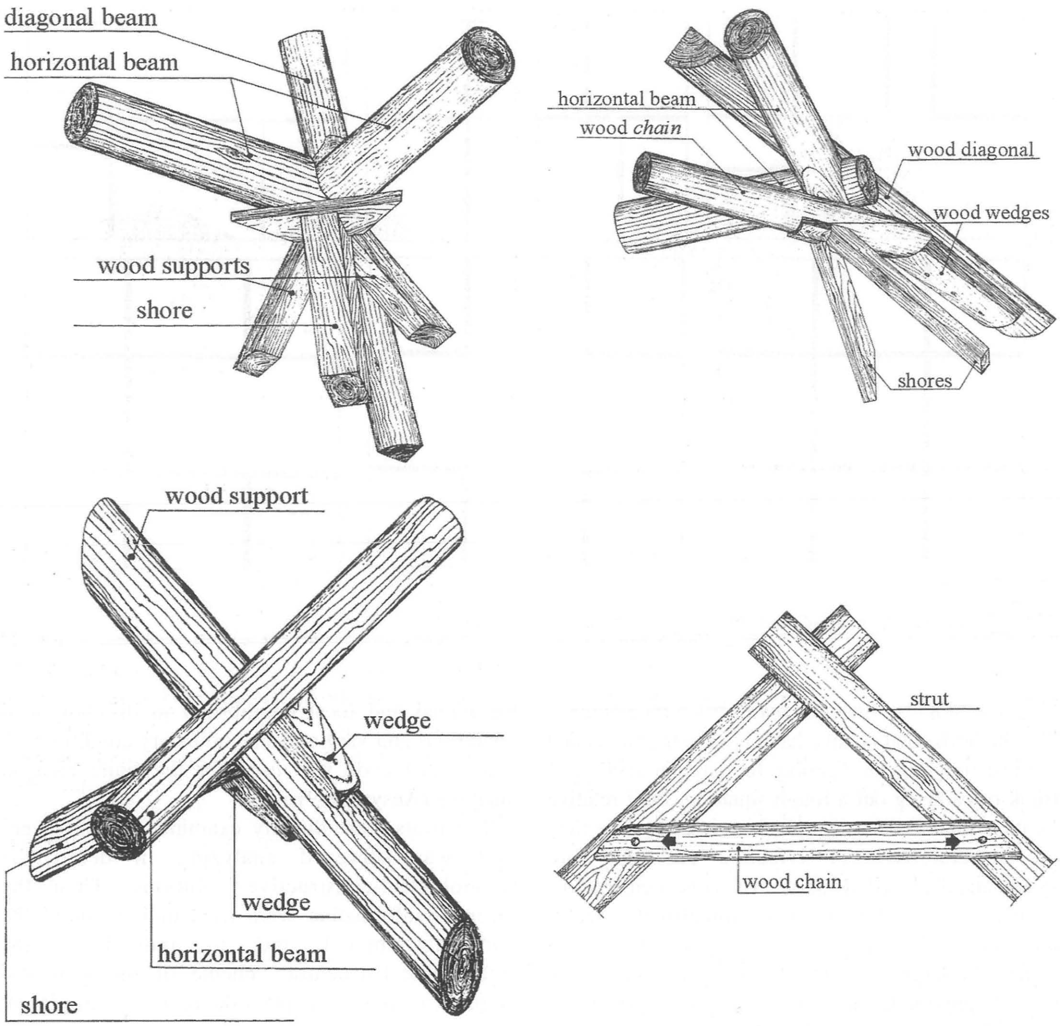

Figure 5
Some examples of joints

is the knowledge of the technological-structural logic of the original Genoese roof structure.

The numerical models were built in the following steps: nodes setting, corresponding to the positions of joints and considering the presence of secondary wood supports and nails; element axis individuation, jointing the nodes; choice of different elements: for the walls (shell element with bending and axial stiffness), for the main structural elements (beam element), for the wood supports (spar element), for the rafters (equivalent shell element with bending stiffness and with mean mechanical characteristics), for the wood planking (shell element with axial stiffness). The slate rooftop was considered as a permanent load; choice of the constraints: equal for every joint between the walls and the wood elements (displacement constraints), perfect support for the wall bottom;.

The following load condition were considered in

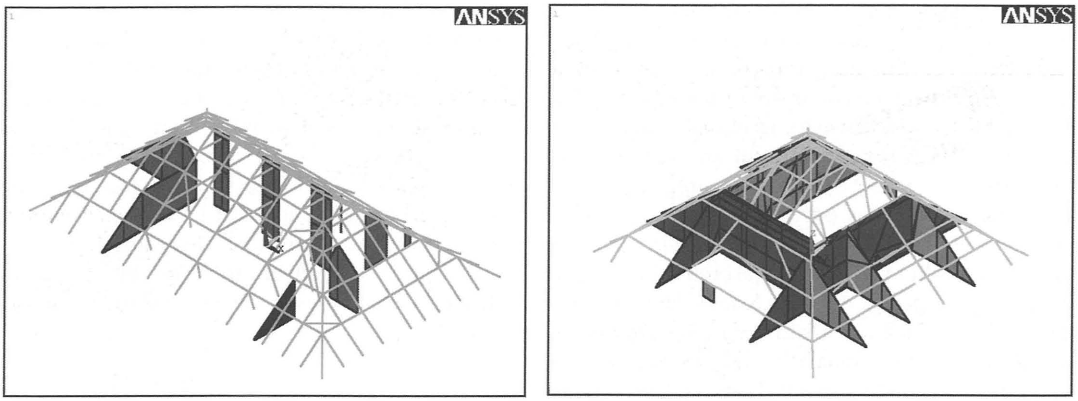

Figure 6a and 6b
Examples of developed numerical models: Musso-Piantelli villa; (b) Grimaldi villa

the simulations: weight of the entire wood structure, the weight of the slate slabs layer (specific weight: 2700 Kg/m^3) and a live load (1 KPa) as vertical load; the wind load (1 KPa) as horizontal load. The two different load conditions were separately examined to emphasize the structure response under the two different load conditions.

Some changes of the model were considered for every roof to study the role of several structural elements: two different manners to model the real joints, considering every element convergent in a joint (*Case 1*), considering the real position of the different elements convergent in a joint (*Case 2*); the rafters and the planking layers without stiffness (*Case 1*) or with stiffness (*Case 2*).

An important general result of the structural analysis is the confirmation of the tridimensional behavior of the roof structure very different to the traditional bidimensional roof structure with trusses. The level of stress and the maximum deflection were low respect to the admissible values of the used timber in every roof structure. This result is mostly important for the larger villa (see) that confirms the big ability of the historical builders.

Table 1. Examples of obtained results in the finite element analyses

Musso-Piantelli villa	σ_{max} (MPa) caso 1	σ_{max} (MPa) caso 2	σ_r (MPa)	f_{max} (mm) caso 1	Grimaldi villa	σ_{max} (MPa) caso 1	σ_{max} (MPa) caso 2	σ_r (MPa)	f_{max} (mm) caso 1
wood diagonal	4.81 –5.12	0.99 –1.02	90 –50	–0.42	wood diagonal	1.73 –2.13	0.36 –0.34	90 –50	0.28
horizontal beam	17.53 –17.99	4.63 –4.53	83 –39	–2.57	horizontal beam	11.34 –11.36	2.34 –2.29	90 –50	–16.2
shores	0.11 –1.78	0.43 –0.38	83 –39		shores	–3.06	0.43 –0.26	90 –50	
planking	1.31 –1.31	0.55 –0.45	95 –50		planking	4.86 –2.43	0.41 –0.24	90 –45	
rafters	0.96 –0.96	0.33 –0.33	95 –50		rafters	1.81 –1.40	0.45 –0.14	90 –50	

The regularity of the main structural scheme and the recurrent technological-structural solutions were observed in two different type of roofs. The rectangular villa present common constructive characteristics and so it is possible synthesize the results in a summary. A central wall and some other wall are used as main supports of every roof structure; particular technological solutions are used in larger zone where the walls are too far to create intermediate supports (rafters, struts, etc.). The horizontal beams rings are the elements that support the main loads. The rafters and the wood planking are a stiffening role. The use of wood supports are common in every rectangular roof and very important for the global structure equilibrium; the more interesting solution is the intermediate wood supports in the larger free zone, analogous solutions are adopted in the three villa, but with different constructive characteristics. Here it is important to underline that often the use of wood supports results essential for the global equilibrium of the structure.

The square villa have a more regular roof structure, in fact they are symmetric, except the use of some wood supports in the greatest one. These kind of roof structure are more interesting for the technological-constructive solutions used. In particular these roof structure are resulted more sophisticated and also more «projected» that the rectangular structure.

A sequence of theoretical models is made in order to synthesize the obtained results and to verify the role of the different structural elements.

In the first one the wall supports, the main beam rings and the roof layers (without stiffness) are considered; in the second one the diagonal elements are introduced; in the thirst one the wood supports are introduced; in the last one the stiffness of the secondary structure and of the roof layers are considered. This final analysis clearly underline the role of different structural elements and how every element are strongly necessary. In fact only the complete structure results correctly stressed, that is on the average every structural elements are equally stressed and the level of stress and the maximum deflection were low respect to the admissible values of the used timber.

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From wood to reinforced concrete. Window manufacturing materials in the evolution of construction technology in Italy in the thirties

Stefania Mornati

The years between World War One and World War Two have been marked by an innovation drive which covered the whole domain of the building industry technology. While the cultural debate focussed on various interpretations of modernity, an unusual interest flared up among designers with regard to buildings technological aspects. The lively research activity entered in those years throughout Europe concerning building materials and technology became intertwined with a broader debate on architecture renewal. In Italy, this took up a trait entirely of its own —the heavy tradition factor bearing down the experimental drive resulting in the uniqueness of the Italian architectural language. New technologies and materials which had just become part of a new building environment were confronted with conventional materials while new uses were being developed for these last.

Trade magazines had accurately underlined new technology research trends since the early Thirties. Many of them devoted extensive space to technical stories and also launched new sections to report on fresh patents for the building industry. Paid space also grew to advertise building materials. A patent number advertised in a magazine would often grant a sort of «added value» to a product as it meant straightforward modernity.

Patents became particularly important in those years. Never before had building designers shown that much interest in patents as such, though they had always»unawares» resorted to inventions in the process of their work. A look at the 1920–40 records of Patent Authority —however peculiar this source may be[1]— shows a special vitality within the building industry. Besides witnessing the experimental climate of those years, this helps clarify the range of relevant research activities in those years (Mornati, 1999a).

Among the various components of a building, window frames are the kind of fixture that makes it possible to verify potential architectural and technological innovation, thanks, among other things, to reinforced concrete frames which by then had become rather largely used by Italian builders, too. In the new structural approach made possible by reinforced concrete, hollow spaces in walls become features of their own as they widen out, thicken or withdraw from the front line, denouncing quite often some new and innovating conceptions of the architectonic body.[2] Such an updating of language, though, calls also for alternate approaches to windows opening, to make large cumbersome wings and shutters more handy and manageable.

Window frames, be they conventional iron or wood, or more up-to-date metallic or concrete ones, will be subject to assiduous and specialised research. In this process, technological innovation will be closely associated with tradition.

Modernization of wooden window frames

In the renovation process of wooden windows, transition to modernity has a lighter hue than in other

types of frames. No substantial modifications to frame stress sections, no new materials innovation is strictly confined to the role of windows within the built body and is marked by a will of conserving the familiarly known character which for centuries had been entrusted to wood.

In such limited, though by no means less lively, circle, studies are directed towards possible surface enlargement of windows as well as to making opening operations easier. Also, to suit windows to the new interior spatiality and reduced thickness of curtain walls. From these walls, moreover, windows tend to become autonomous even under a construction point of view. Last but not least, efforts are made towards mass production.

A need for mass production had already surfaced in the early Twenties, since a proposal for an enbloc (fig. 1)[3] window frame is filed with Patent Authority in 1922. Contrasting with the newness of the approach, the pictures show a conventional window frame with a shaped stone edge. The window features also outside blinds and inside shutters. The invention lies in the possibility of disengaging the frame from masonry works as well as in an innovating open-close mechanism as all wings are sliding through a hollow space and can be controlled from inside.

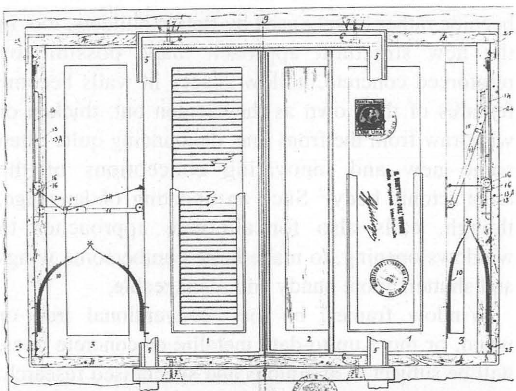

Figure 1
E. Cattaneo's enbloc patented window

Only few years later, G. Pagano and G. Levi Montalcini designed Palazzo Gualino (1928–29), which is believed to be the first Italian Razionalismo work. Here the new technology of horizontal slit windows —promptly called «in bed» as opposed to conventional vertical range ones— is an evidence of openness to experimentation, though within the boundaries of a classically paged up façade (fig. 2).

A horizontal window can fully span across bearers and allow for ample brightness and ventilation of premises. But only if combined with an up and down latching system this kind of window becomes suitable for modern interior layouts and decoration. Up and down control systems —which were to attract large numbers of patent applications— are the most fit for horizontal windows —no shutter gets in the way, windows can be placed at building corners, walls are fully usable up to the very window. They also fill health requirements for they allow for gradual air change. Moreover, they innovate shading systems because they suppress conventional blinds and shutters and introduce roller shaders.

The story of the large wooden frame —over 13 ft. long— which was manufactured for the front of Casa del Fascio, in Como (G. Terragni, 1932–36), is eloquent in this connection. The early proposal wanted it to be made out of drawn iron but it was rejected because it didn't suit the idea of a whole span clear of posts, nor the need for an up-and-down latching system. This, in turn, was a must in the light

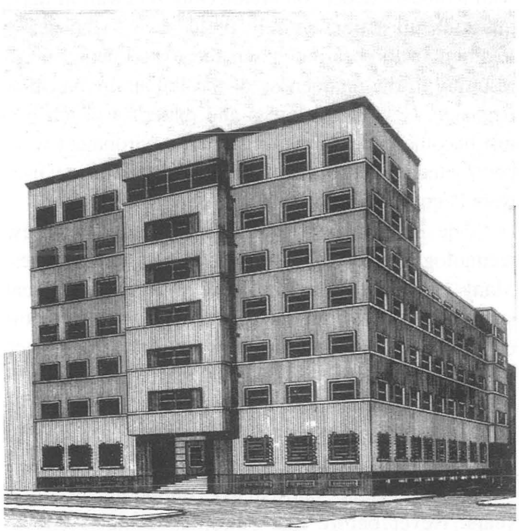

Figure 2
Palazzo Gualino in Turin (G. Pagano, G. Levi Montalcini, 1928–29)

of the frame unusual size, but still little tested as an iron structure (Poretti, 1998). A wooden frame with no middle posts was eventually chosen. It included three overlapping wings to be controlled through three hempen belts and a sash weight mechanism patented in those years by Colombo & Clerici Co. —the same Firm which was to manufacture the whole rig (fig. 3).[4] In this story, the reasons of function are associated with a will for continuing a building tradition that often accounts for the use of most common materials, not only in high profile projects but also in such housing programs in which simple common taste is reflected —all this helping outline the character of Italian architecture between the two wars.

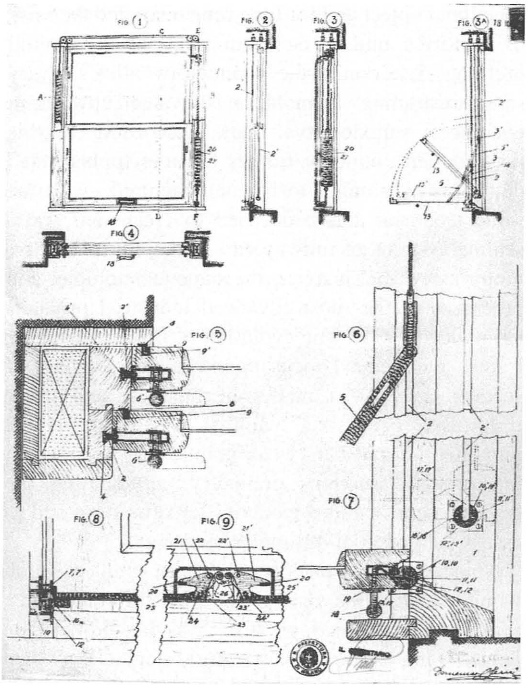

Figure 3
Colombo & Clerici's patented frame, 1933

Terragni's building severe and monumental façade will therefore be finished off by wooden windows, while more modern materials such as steel will be left to courtyard prospects (fig. 4).

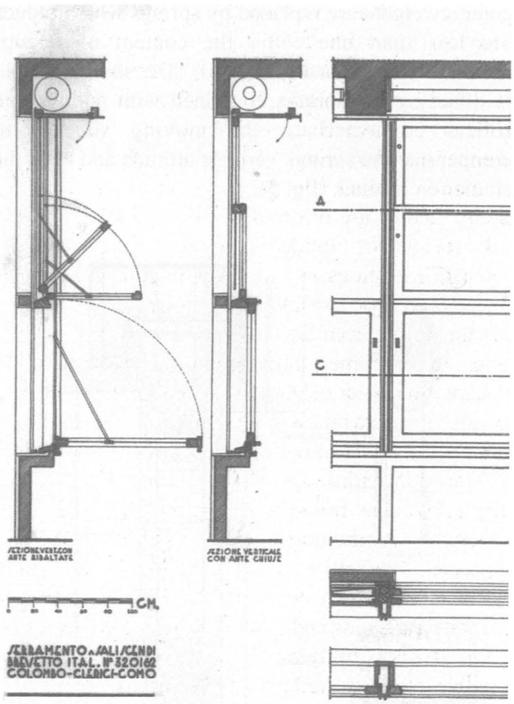

Figure 4
Como Casa del Fascio window frame (G. Terragni, 1932–36)

In the autarky years, wood —like any other material— had to undergo a close evaluation concerning its economic dependance upon foreign supply. Most of lumber used for fixed or sliding frames and for shutters and blinds used to come from abroad. Potential alternate material could be a mix of resins and bonding agents with sawdust, chips, shavings, wood flour. Some agricultural by-products such as hemp processing waste were also considered for use[5]. Together with these low-feasibilty proposals, more realistic ideas are found in the records of the patents office. And they are such as could not only make window frames and related controls safer and lighter, but also help the country's economy since the iron content of mechanisms is reduced. Such is the case of a wooden window frame[6] which was advertised in the magazine «Casabella» as a «home product» —its cumbersome and expensive

counterweights are replaced by springs which reduce «to less than one/tenth» the content of ferrous materials in it (Matricardi,1940). The shutter weight is offset by the springs combined with pulleys and rollers connected to the moving shutter, to compensate the springs variable attitude and keep the shutter on balance (fig. 5).

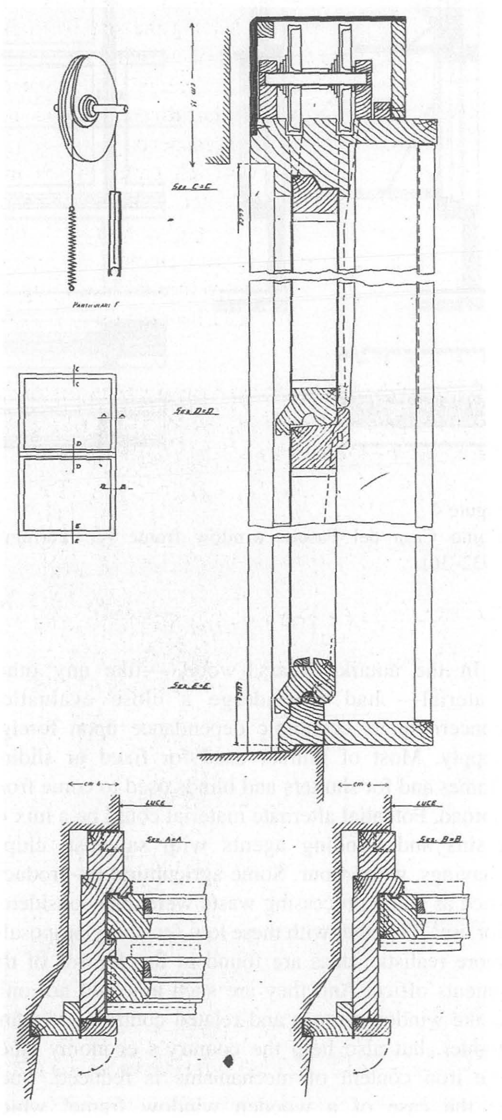

Figure 5
The autarchic wooden frame advertised in «Casabella»

Evolution of metallic bars

Metallic window frames have been used in Italy since 19th century. Though they don't have a multicentury history, like wooden ones, they can be considered quite ordinary stuff. Their use is closely related to the development of the iron industry which has made mass production of hot drawn bars possible since mid —Eighteen Hundreds. Available sections then were Z, L, T. They were called «normal sections» and used to be welded or riveted together to form the joints and ledges to fit in glass panes which used to be puttied in.

Higher structural capability than wood, incombustibility, non-deformability made metallic sections a market success. Still their origin from a strictly industrial process stamped them as a merely functional object and for long time restricted their use to factories and to service areas of residential buildings. Later on, in the Nineteen-twenties, the very same «restricting» connotation is revalued upwards to become a «modernity» mark. According to this reassessment, window frames become sophisticated devices which ought to be manufactured «with the same technical standards used to create air/ water sealing systems of railway cars, large aircraft, ships, motor cars», that is to say the same technologies and processes of the most advanced industrial products (Minnucci, 1931). The evolution of metallic window frames will indeed focus upon the development of section bars. As a matter of fact, air and water tightness, eccessive weight, deformabilitystill remained normal bars weak points, driving research to articulate sections geometry, anticipating the development of more modern «ferrofinestra» and to assess the potential of tubular sections.

Since the Tens, patents have been granted which would improve the glass-frame joint. More complex sections were studied, air space was created between ledges using elastic seals, structural steel was coupled with rubber to ensure airtightness (fig 6).[7]

Tubular sections begin to show in the patents file of those years. Their purpose is to combine air/water tightness with the maximum possible lightness.[8] These early innovations help define the steps needed to upgrade the component performance. But only the launch, in the Twenties, of a special section bar called «ferrofinestra» or «rationale section» would allow a marked improvement in window frames performance.

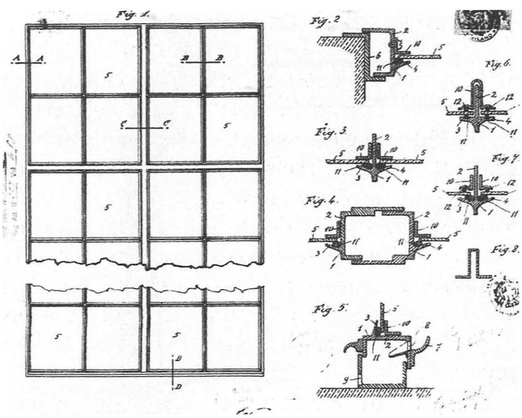

Figure 6
Metallic frame patented by C. Aiolfi, 1916

The new section will become a modernity symbol thanks to the innovation of its manufacturing process based on mass production of few section series suitable to fit all types of window frames —with the ensuing factory organization.

Ferrofinestra was already widely used in more metal-rich, metallurgically advanced European countries. It is introduced on the Italian market with the backing of foreign producers who guarantee initial supplies until Italy's industry becomes capable to hot-mill perfectly linear, complex section, accurately processed iron bars. Materials involved are Martin-Siemens steel and rust-proof copper steel.

Compared with conventional section bars, ferrofinestra is cheaper, lighter, more indeformable. It also allows better tightness and durability. Moreover, it improves premises brightness since no heavy fittings are required as with old bars —one bar fits all building requirements.

Italian industry furtherly refines ferrofinestra design. ILVA, for one, rounds off sharp edges. This improves protective coating adhesion. They also move on to wedge-shaped wings, which improve surface contact compared to parallel wings.

However modern, and differently from what happens in Northern Europe, ferrofinestra is not to become a bestseller with Italy's standard building industry. Basically, it will be used for its structural qualities —that is large window walls of institutional buildings. Still, whenever its qualities do not justify its use, ferrofinestra will be used in secondary prospects.

As a matter of fact, it is emblematic the use of ferrofinestra in such important buildings of the Thirties as Scuola di Matematica in Rome Città Universitaria (G. Ponti, 1935–35). Here ferrofinestra, associated with a further modern material called Termolux,[9] is used on the fronts of a most modern part of the building which, however, sits in the back of the whole project, thus leaving the stately, higher profile main façade to wooden window frames (Mornati, 2002) (fig. 7). In G. Terragni's masterpiece, Como Casa del Fascio, too, ferrofinestra is confined —as we said— to courtyard prospects.

Beyond bar sections, research paths stretch into metallic windows opening ways. A large number of patents cover this issue. Weight is always a main factor, for it is a test-conditioning element. As regards normal size windows, conventional swinging or transom openings are confirmed; up-and-down

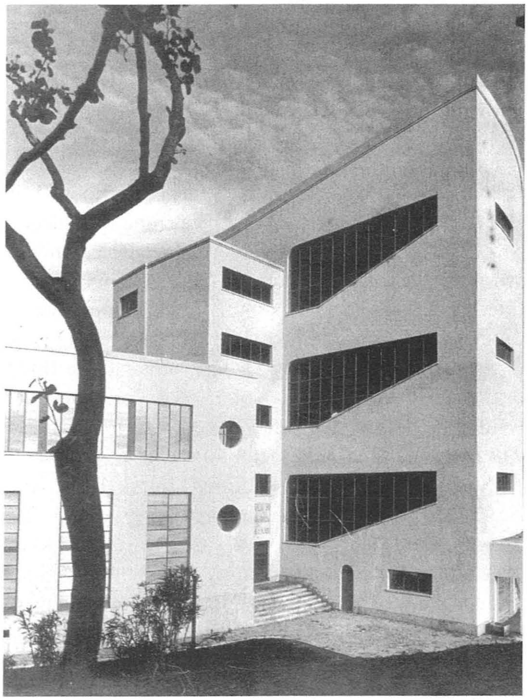

Figure 7
Metallic frames of Scuola di Matematica's secondary section at Rome Città Universitaria (G. Ponti, 1932–35)

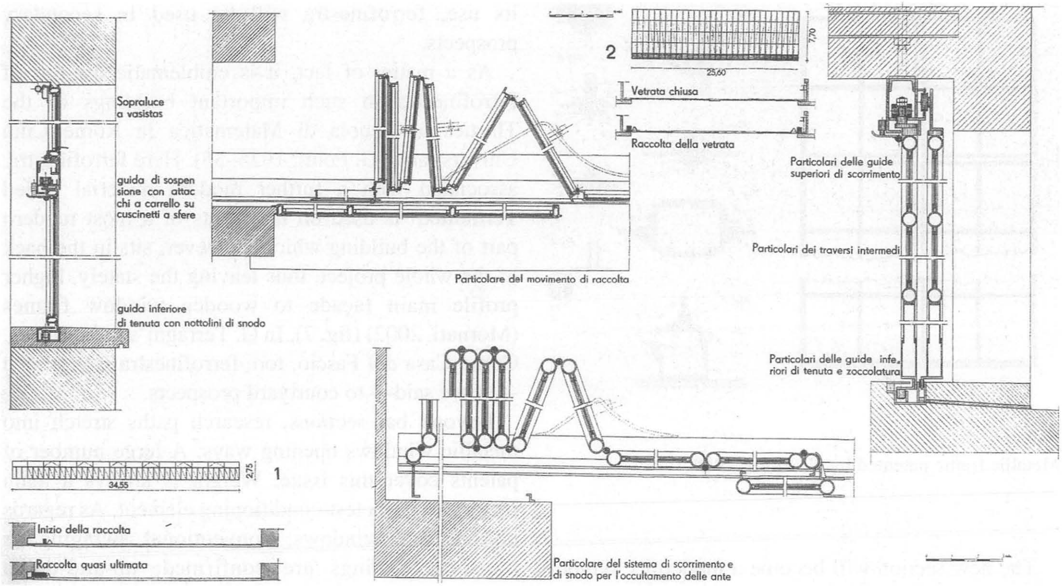

Figure 8
Curti Co.'s 1931 patent as shown in «Casabella»

latching systems are unusual. The biggest innovation will occur in larger glazed frames, where «book opening systems' are tested. In this connection, Curti Co., one of Italy's best known iron frame producers, gets (1931) patent rights covering an iron window system with foldable frames[10] (fig. 8). This will be fitted few years later at Bologna Istituto Superiore di Ingegneria (G. Vaccaro,1935) and will include ferrofinestra sections (fig. 9). The same will be fitted in the indoor swimming pool area of Forlì Casa del Balilla (C. Valle 1936), where Mannesmann tubes will be used (L. S. 1936) (fig. 10).

Studies on hollow sections pursued in the beginning a number of aims. Among them, less weight, less deformability, no elasticity loss, possibility of inserting insulating materials in cavities to improve the frame thermal resistance. Efforts were also made to reproduce wood familiar profiles in section bars.[11] These studies were furtherly promoted, as was research on light alloys,[12] when Italy entered the autarky period. Following this, what had been an advice to reduce imports of building materials, becomes a prohibition.

Ferrofinestra, too, is then subject to close economic scrutiny and the result is that its use reduces iron needs by 50 percent against normal iron section bars (Bartoli,1938). Ferrofinestra is since declared the most autarchic frame material (fig. 11).

Import restrictions, however, must have quite light an impact if, at the peak of the autarky stage, ferrofinestra is used in large quantities for the 168 imposing glass windows of Palazzo della Civiltà Italiana (G. Guerrini, A. Lapadula, M. Romano, 1939–43), not confined —this time— to minor prospects. Although in this building history, attempts are made —with no results— to dignify iron with some more valuable coating, those large big windows still stand out with their stern look in line with the building image. In this work, however, no studs slightness is pursued and a 50 mm. Ferrofinestra section is used, that is the largest available profile in ILVA sections stock. Such bar is assembled in a threesome arrangement resulting in a total 10 cms. section, thus bestowing on window frames the same monumental character of the whole building (fig. 12).

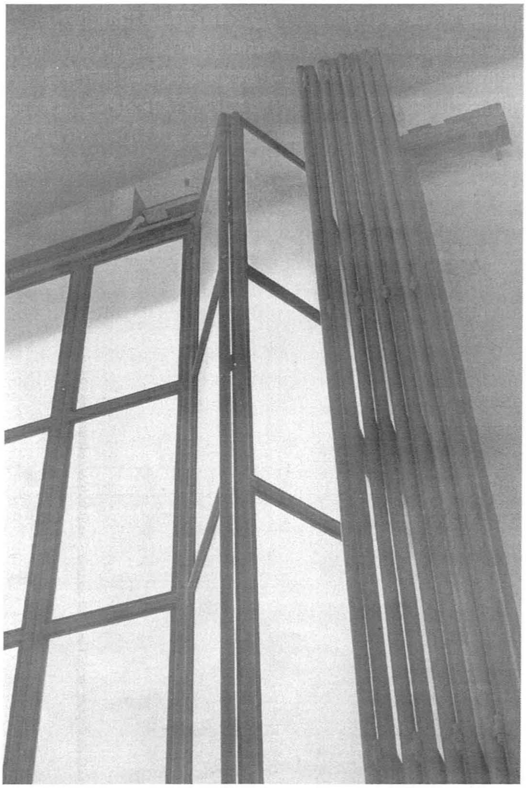

Figure 9
Detail of foldable sliding wings of the Scuola Superiore di Ingegneria glazed windows in Bologna (G. Vaccaro, 1936)

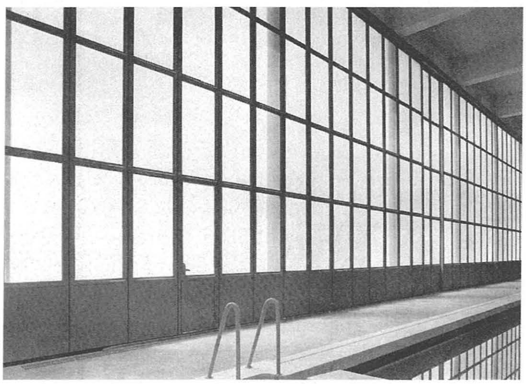

Figure 10
Foldable sliding wings of Casa del Balilla glazed window, in Forlì (C. Valle, 1936)

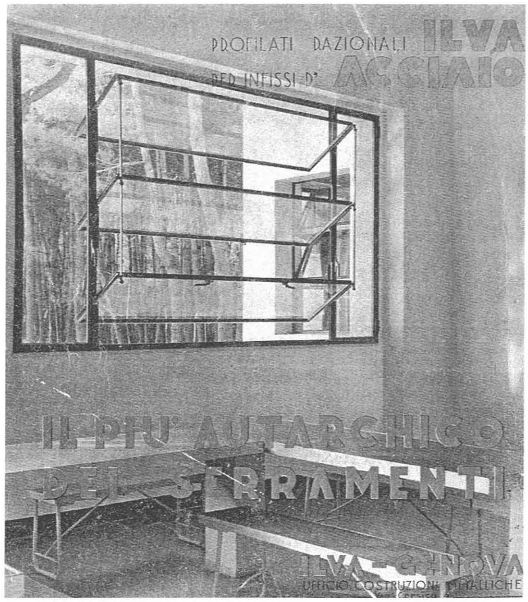

Figure 11
An ILVA advertisement appeared in «Casabella», nos. 138–139–140, in 1939

«Liquid mire»

Thus Ugo Ojetti would synthesize his disdain for the popularity enjoyed by reinforced concrete in Italy —as well as elsewhere— despite the harsh debate that came with it (Pagano, 1935). Though this material was routinely used in the Twenties for load bearing structures and various construction elements, its use for the production of window frames was not as widely accepted. The scantiness of research in this sector is reflected in the small number of patent applications filed with the office and, most of all, in the little use of reinforced concrete frames (Mornati, 2001).

Ordinary glass panes coupled with concrete bars had been used, since the Twenties, to produce transparent coverings imitating better known metallic or wooden carpentry. Likewise, the first patented swinging wing frames —their French origin is proof of their wider use over there— are only transferring standard concrete technology into conventional patterns as far as look, bearing sections and opening

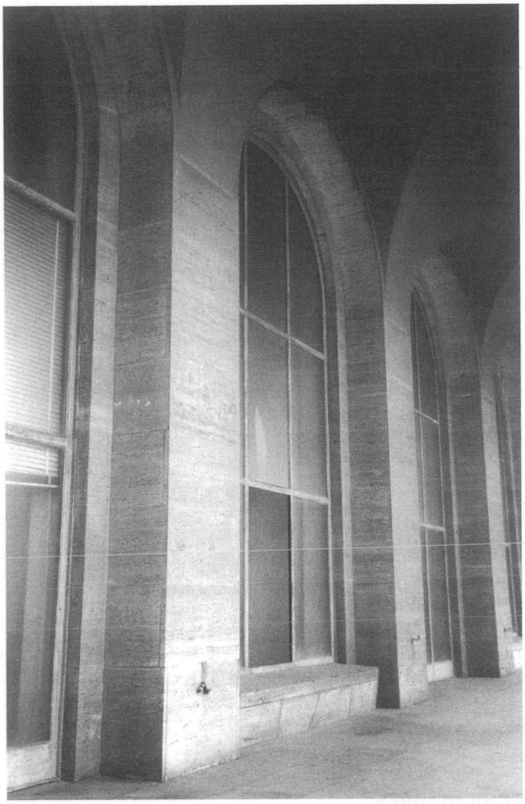

Figure 12
Sequence of large window frames of Palazzo della Civiltà Italiana in Rome (G. Guerrini, A. Lapadula,M. Romano, 1939–43)

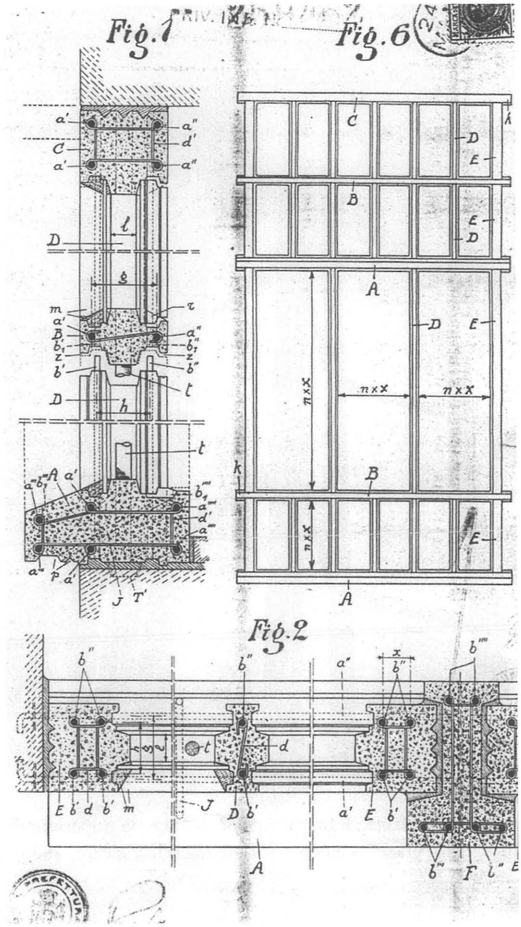

Figure 13
A picture of the French patent for reinforced concrete window frames, 1927

systems are concerned. No consideration is given to material different mechanical capabilities.[13]

Some interest arouses about concrete frame transparent walls as an alternative to concrete and glass tiles which permit traslucid walls, as shown in one of the most up-to-date handbooks of the Thirties (Griffini, 1932). The early instances consisted of large-size prefabricated monolithic frames which were assembled with the help of a falsework. Problems of weight, on site storage, handling and breaking risks of such cumbersome elements eventually suggested to break them up into shorter linear pieces which would be held together by protruding stress rods or pins[14] (fig. 13). This approach allowed to realize glazed frames of all sizes, very much like concrete and glass tile technology.[15]

Still, G. Minnucci, with direct reference to glazed walls, while illustrating the good qualities of reinforced concrete frames (Minnucci 1929), stressing their fine economics, low maintenance requirements, incombustibility, weather-proof ability, declared them more suitable for industrial buildings.[16]

Among the very few uses of this technology, one peculiar instance are the two series of five large «pumice concrete' glazed windows made for Rome

Palazzo della Civiltà Romana (P. Aschieri, C. Pascoletti, D. Bernardini, E. Peressutti, 1939–43) (fig. 14). Here, too, an evidence of modernity is confined to side prospects, leaving to the mighty blind walls of main façade to stand for the Museum institution.

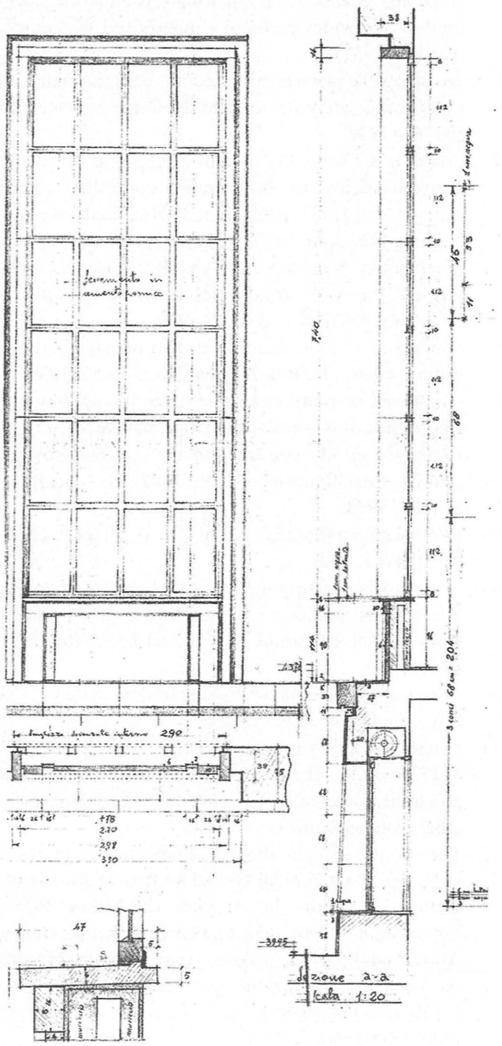

Figure 14
Pumice concrete window frame, Palazzo della Civiltà Romana, Rome (P. Aschieri, C. Pascoletti, D. Bernardini, E. Peressutti, 1939–43)

Pumice concrete is a mix of Lipari pumice grit and Portland cement, reinforced with 3–4 mms thin rods tied with iron thread. The mixture is cast into dismountable scagliola boxes so as to get a very fine surface dressing. Window frames produced with this technology are as light as ferrofinestra ones (15 kg/sq.mt.), and feature good strength and mechanical resistance (Albert, 1939). The windows of the Palazzo building are 7.40 ¥ 2.98 mt sized, they are divided into 4 horizontal and 6 vertical spans and carry vertical and across hexagonal bars. One of the horizontal spans is made of transom windows which can be opened thanks to metallic sub-frames. Reinforced concrete swinging wings are indeed a problem, not only because of their weight but also for the awkward connection between hinges and frames and the material brittleness in the areas of hinges and edges connection.

The only truly innovating proposal comes in 1939 from G. D'Aronco, a scholar from Friuli who researched various reinforced concrete applications. Different from other researchers, who would fit (new) materials to conventional, long tested control systems, he filed a patent application for a window frame where a combination of flexure, cut and torsional stress is the solution. Together with a cross bar section —«which best suits an iron-concrete combination»— and a quite fluid, finely batched mixture which allows thinner sections, D'Aronco deviced a complex control system which does away with side hinges and has the wing rest entirely on a mobile bearing, lower down,which is hinged on to the wall below the window.[17] This way the wing and the frame are stressed only to the extent needed to ensure frame airtightness (fig. 15).

As far as reinforced concrete is concerned, research on building materials with a potential to satisfy the autarky environment, focussed on cutting down iron use. Odd proposals were put forward such as resorting to bamboo canes to take up tensile stress.

On the same line, research on tubular metallic sections comes now handy to manufacture a new profile called «metalcemento». This is made up of stainless tubular elements (other materials are also usable such as asbestos, cem, synthetic resins, plastics) which can be coupled to each other to reach required sizes. Cement is cast in between over a metallic bracing to make a stiff, monolithic block. Iron requirement is slashed down by a 1 to 20 ratio

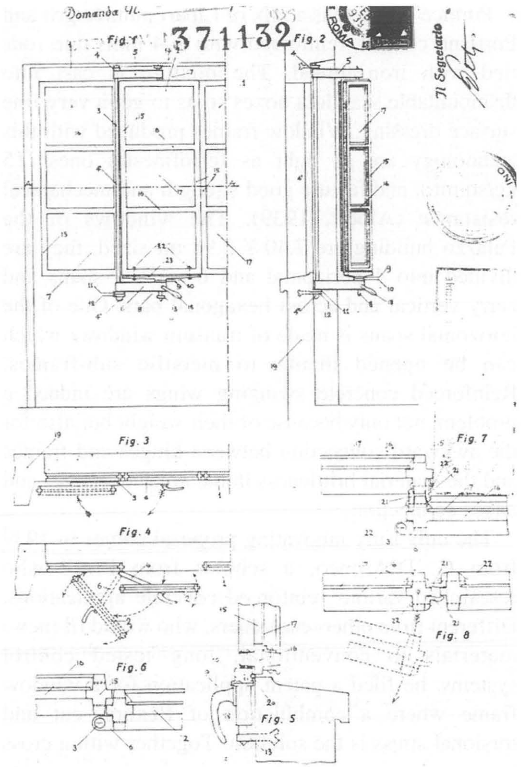

Figure 15
G. D'Aronco's patented reinforced concrete window frame, 1939

compared to metal frames (Diotallevi and Marescotti, 1940).

As regards current building practice in Italy, concrete window frames will be used almost exclusively in residential projects. This bears witness to their utilitarian vocation. The use of concrete window frames in other types of buildings must be considered as some sort of promotion of involved materials modernity, devoid of any architectural value whatsoever. This confirming, at several years distance, Minnucci's perplexities.

Notes

1. Materials of Archivio Brevetti (Patent Office files), from which the patents we described were drawn, is kept at the National Central Archives's, Patents Fund. We would like to remark that such materials are a very special source for researchers because —although many proposals have been used by the building industry, many others remained in a theory stage, without a market outlet. And this describes the invention's limits.
2. Still in 1937, Pagano comments on reinforced concrete potential of use: «Descending from such technology of skeleton structure are the rhythm of long-footage horizontal windows, the pillaring layout as well as the rhythm of wide-spanning, superposed balconies». (Pagano, 1937).
3. «A complete mechanical window featuring automatic locks and a safety device», by E. Cattaneo, Patent No 203761, 1922.
4. Colombo & Clerici Co. filed in 1932 patent No. 307018 «Improvements to bi-laterally controlled sliding windows». In 1933, patent No. 320162, under the same heading. For more details. (Mornati, 199b).
5. «Elementary window frame profiles and decorations formed through wooden concrete pressing», by E. Adami, patent No. 374412, 1939.
6. «Improved window frame with two or more vertically sliding wings», G. Rossi, patent No. 370852, 1939.
7. «Improved no-putty locking systems for window glass and frames, in general», C. Aiolfi, patent No. 154361, 1916; «Mode de construction de fenetres, portes et chassis metalliquest», A. P. Dousse», patent No. 219305, 1923.
8. «New window framing system», by P. Marchesi, patent No. 194782, 1921.
9. Termolux is a diffusion glass with thermal and acoustic insulation properties made out of two layers of stretched glass plied to an inside glass thread layer (Repertorio, 1934).
10. «Vertical foldable frame shutting or door system», Curti S.A., patent No. 303973, 1931.
11. «Metallic window or door frame», C. Grassi, patent No. 311736, 1932. The invention description stresses the possibility of coming up with the «same look as any other wooden frame».
12. The success of light alloys had been helped by the the large use of anticorodal special sections, particularly in connection with the frames of Milan Palazzo Montecatini (1936), due to Ponti, Fornaroli, Soncini. Anticorodal is a silver hue aluminum alloy mechanically comparable with extra mild steel. It is highly stress resistant as well as weather and chemicals proof (Repertorio, 1934).
13. «Chassis en ciment armeé pour fenetres a guillotine», J. Clément, patent No. 194593, 1921.
14. «Glazed windows brushing, molding process and tooling», Le Chassis en ciment armeé M. T., patent No. 258452, 1927.

15. As a matter of fact this patent was taken over by S.A.I.V.A. in 1939. Società Acc. It. Vetrocemento armato is a well-known corporation which has operated in the glass tiles sector since 1899.
16. Minnucci believes that concrete window frames are overly heavy but still a good value. Therefore they could used in low-cost housing projects, where economic factors are most important.
17. «Double-hinged fitting system for concrete glazed windows frames, allowing for perfect weather-proofing», G. D'Aronco, patent No. 371132, 1939. D'Aronco will also get patent rights for collapsible formworks to produce window frames. Still on the occasion of his own house expansion, Mr. D'Aronco resorts to concrete frames not based on his patented system, choosing to link wings and frame by means of conventional hinges. This is indirect proof of the theoretical nature of his research and rather uses (Mornati 2001; Bertagnin, Chinellato e Tubaro, 1999).

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«Construction history» and «Construction of histories». University education and the future of construction history

Stefano F. Musso

When we try to understand how and, above all, why the ancient people built with certain materials, forms, structures and techniques, we have to reflect, first of all, about some methodological aspects that we can synthesise as following:

- Are we dealing with the history of building art development or with the history of single, even numerous, buildings?
- Are we considering history as a simple tale, or are we working on a history like a problem? (J. Le Goff).
- Is it possible to write a history of the past events and of the traces that these events left to us from the point of view of the past cultures, or are we compelled in constructing a history always from the present perspective? (B. Croce).
- While we are studying this particular field of human activity, are we involved in a history of the long lasting or in that of the sequence of different events? (F. Braudel).
- Could we really believe that it is possible to construct a history free from any constraint and able to deal with everything belonging to an unknown past, or are we obliged to select, every time, a particular range of events or singular fragments of what happened in the previous ages?

In any case, as these questions clearly show, we have to compare our efforts, in the field of the Construction History, with all the achievements of the Historic Sciences in general. In other terms, we must recall and respect the deep development of these kinds of studies, at least during the past century, because we work within the same conceptual co-ordinates.

All the possible answers to the mentioned questions, further on, are strictly related to other important problems. We could for instance recall the different sources, direct and indirect, ideal and material, that we can use to investigate the past conditions of the buildings, or to «construct» the history of building art and techniques.

We must also decide if we are trying to build a Construction History, as a contribution to the general advancement of human knowledge, or if we aim to investigate a specific segment of the past. More over, we have to ask to ourselves, if we study and research just to discover and to understand or if we want also to use the results of our investigations to preserve or to restore the ancient buildings, for example. All these are, in fact, very different and in some way, opposite perspectives for our efforts. It is a deep difference already put in evidence, for example, by Manfredo Tafuri, when he criticised the idea of an «operative history» and invited all the historians, and above all each one who intends to study the past, to respect the free and open character of any historical enquiry.

The paper proposes some matter of reflection on these and on other similar problems, to open a

conscious discussion about the possible perspectives of a Construction History. All the themes faced in this contribution are especially regarded under the point of view of their theoretical implications, which are so important for the research and within the university education system of the future.

We can so start from a sort of contradiction, or a paradox, that each historical enquire meets, before or later, and that more than others every study of the architectural heritage does.

We can argue on this contradiction recurring to the following sentences.

A BUILDING IS AN ARTEFACT BUT IT CANNOT BE EXAMINED ONLY AS AN ARTEFACT

A culture, first of all, can never be reduced to its artefacts, while it is being lived. This is always true but, if it is possible, it is even more true apropos of the artefacts that every culture, every social group and each age produces to satisfy its need of safety, life, work . . . and that we generally name as «architecture» or «constructions».

Yet, when we deal with the history of the past civilisations, we always investigate, study and hope to understand only and exclusively the artefacts they left us in heritage, sometimes with willing but sometimes also for mere casualty.

This is the first great problem we must keep in account during each step of our work. Dealing with the Construction History as consequence of this particular condition, in fact, does mean dealing only with a segment of the general history, because its objects of interest are only a part of the artefacts created during the past. Moreover, any attempt to investigate these objects, the buildings and the constructions of the past, must recur not only to the buildings themselves but also to the other and related artefacts produced in the same periods, by the same men, such as books, instruments, mechanisms, manuals . . . and so on.

Therefore, one of the most difficult task confronting us, in any historical enquiry within this field, is perhaps the complicated process of evaluation of the inherited traditions, of the theories but also of the practical actions that signed the way which our ancestors built in.

We know in fact, that a building is always a complex product of a wide world of knowledge (not only technical), of needs (not exclusively material), of willing (not always conscious) and of many others components of the construction processes.

We also know that a construction represents and occupies a sort of boundary between the world of nature and the artificial world of culture.

For all these reasons, a real understanding of what a building was and still is, is very difficult, not to say impossible, just because we lost all the evidences of these different components of the process that created it. We really possess only their material results, and we can study them only in the state they have been modified in by the time that divides us from the moment of their construction. The natural time, with all the decay phenomena it brings with itself, and the cultural time, with all the human actions that, in every moment of the history, express and make effective the intentions of modifying the world and the things inherited from the previous ages.

This particular situation makes everything very complicated for our attempt to investigate and to understand the history of a construction.

Our efforts to understand how, why, and for what reason a building was constructed in a particular way, begins even more complex when we enlarge our attention and when we spread off our researches towards others buildings. We always try, in fact, to face the architectural products of a period, of a region or, at the end, the whole construction history of mankind. Now we must recognise that, perhaps even only for the mentioned questions, this result appears to be almost impossible to be achieved.

INVESTIGATING THE PAST HISTORY AND NOT DEALING WITH THE HISTORY AS A SIMPLE TALE

The fundamental doubt that these simple critical elements provoke is that, under certain respects, we always risk not to enlighten the past history of a construction, or even that of wider ensembles of different buildings, but to really construct their past history.

The difference between the two situations is, however, of enormous importance and it has great consequences. The limit between the acceptable and the unacceptable, on this field, is really thin, and in the second perspective we could risk to superimpose

to the products of our ancestors' construction abilities a overview completely declined only in present terms, denying every real chance of understanding.

With evidence, in any case, it is exclusively in our responsibility not to follow this dangerous path that could bring us in a sort of court-circuit between the needs of knowledge and the willing of intellectual power.

Thus, we have to decide if our charge is only to deal with what we suppose happened during the past centuries, within the construction of a single building, or inside the construction processes of different periods and regions. The real alternative to this limited purpose is that we intend our work as a continuous excavation, both of the material or direct sources, and of the indirect, written or iconic ones. These are, in other terms, the single buildings and the ensemble of other artefacts, which testify the wider world the different buildings were born from.

Within this second perspective, our enquiries will primarily be more the expression of the willing of finding the real matters of discussion, the problems involved by the attempt in understanding the past, than the ordered result of a sort of great fresco of what happened.

In fact, we can not read the traces of the past centuries thinking with our actual conceptual co-ordinates, simply trying to give an order to them. We must, first of all, ask to ourselves if this order, that is only a result of what happened and that we now try to understand, could be useful for this task or if it will be a sort of impediment. The order, if any one exists, will be found only at the end or during the difficult and never ending development of our researches, following the efforts of an entire scientific community and for many future years.

What has already happened within this field, during the past decades, clearly shows us that every «eventual» Construction History can only be a problem-solving path. It can not be a simple description, or a mere tale of what, in each unsure step of this adventure, we suppose happened in past construction modes, methods and products.

Many documents, conserved in the archives of Genoa dealt, for instance, with a particular argyle, the «Kaolin», used in the construction industry of the ancient republic, but the name of this material was not clear and, above all, there was no evidence of its use. Tiziano Mannoni, one of the founder of the modern archaeology of the elevated structures, tried then to investigate the ancient piers of the historic harbour and to analyse with laboratory tests the consistency of the mortars used in them. He discovered, in this way, that the kaolin had been really employed for their construction, to give the mortars the requested behaviour of water resistance. But the ancient builders, for sure, did not know the chemical processes that ensured these results, because the chemistry was born only during the XIX century with the work of Lavoisier. Now we can easily explain the effective role of the kaolin, thanks to those scientific paradigms, but if we stop us to this kind of interpretation, we can not say having really understood anything of the construction history of those ages. If we really try to understand the characters of the way of construction in each period and in every place, we must in fact understand why those builders used this material, starting from which kind of empirical knowledge and experience, which places and sources they derived from. We have to discover which bases they founded their sureness on, which traditions and workers formation they appointed and used to ensure the spread off of the skill necessary to realise those kind of artefacts. At the end, it is not sufficient, even if it is important, discovering the use of a particular material or dealing with its use, finding general evidences of it. It is more important, but much more difficult, to really understand its role within the processes of that construction culture of the past ages.

Similar observations could be carried out thinking to the structural problems and above all to those involved by the dimensional determination of a wall or of vault, when the modern scientific and technical calculation methods did not yet exist. By the way, it seems to happen in this case something similar to what is often dealt about the inventor of the helicopter. It seemed impossible to the investors he asked the money to realise it that a machine could fly remaining immobile in the air. He noticed then that the bumblebee because the aerodynamic laws could not fly but it does not know these principles and then it normally flies. So we could say that basing our verifications on the modern laws of the construction technique, we would declare that several ancient buildings could not stand anymore. Fortunately these monuments last from many centuries and they obtained the best resistance test just from the time

past till now. Nevertheless we often doubt even of what we see and pretend to change the reality using our provisional and imperfect intellectual instruments, and this could be a real problem for any future Construction History.

«Langue» or «Parole», tradition and innovation, sudden events or lasting phenomena

If we are trying to discover or to re-construct the history of a single building, we could think that the real matter of discussion is represented by a single event or by a limited number of events. It could seem that we are investigating, with all the tools and devices belonging to the modern science and technology or using the most updated analysis and diagnosis methods, could be reduced just at itself.

This is not true or realistic.

First of all, even that single building is not the unique representative of a genre, it is not the only men's product of that particular age or place. Each building is evidently the result of specific conditions, demands, willing and needs and, under this point of view, it is special and unique so that it can not be reduced to any kind of typology, category or general essence. It is just what it is, how it was thought, designed, realised and modified during the years by nature and men, that is by the time passing with all its natural and artificial consequences. Nevertheless, each building, that specific building, is, in the mean time, the result of a wider «culture», of more general aspects, knowledge, abilities that involve more people, social actors, workers, professionals, inhabitants, administrators and so on. It is, in few words, an individual belonging, almost every time, to a reality that involves the collective dimension more than the individual one. It represents the answer given to a specific problem within the great world of the similar answers given to similar problems. Thus, the single building is, in the same time, something special and something common, unique and general: we have only to discover and to establish in which proportions these different conditions play together and reciprocally. But this is not a simple goal, as we easily experiment every time we study an ancient construction.

In other words, as the recent development of the historic sciences clearly puts in evidence, we are constantly compelled within the dialogue between what is general, or «nomotetic», and what is unique, or «ideographic» (just to use ancient but recognised concepts of the XIX century philosophy of history). In the mean time, recalling the same reflections and the same sources of theoretical and methodological elaboration, we are always facing the apparently opposite nature of the history as a succession of single events or as a continuous development of enduring phenomena.

Recalling the linguistic metaphor, sometimes used during the last century even related to the architectural production and expression, we are often called to recognise and distinguish between what belongs to a common structure and what constitutes a personal and individual contribution to the never ending development of a language. The first component is what Fernand De Saussure called the «Langue», and represents the stable structure of a language, that last for long periods and allows the reciprocal understanding of the people belonging to the same community. The second component is what De Saussure on the contrary designed as «Parole» and it represents the contribution that each speaking people of the same group brings to the common structure of the «Langue», ensuring the individual expression but also its development in the time and in the space. Something similar, then, seems to happen also in the construction field, at least for someone, signing its evolution or its changes, quick or slow, localised or generalised, in the time and in the space. It is, in different terms, a sort of reflection of the eternal dialectic existing between tradition and innovation, academic or spontaneous reproduction and casual or willed invention. All these terms naturally and inevitably belong also to the history of architecture, in an enlarged conception, or to the world of the construction methods, materials, techniques, habits, behaviours . . . etceteras. It is sufficient, in this respect, to think at the role of the tradition within the ancient world, till the beginning of the XX century. We can not ignore, in fact, how it was settled and transmitted, from generation to generation, by the «guilds» of workers of the different «arts» (in the medieval meaning of the term), or by the ancient educational and training systems. Everything seems to declare that these facts had the nature of enduring phenomena, interested by slow changes, impossible to perceive during a single life

and very far from any contemporary idea of evolution. The mechanism of the knowledge transmission, within the «bottega» (the ancient laboratory of the artisan) or the construction site, using the examples, recurring to the said words, more than to the written and formalised ones, seem to play a similar role. The patient and always similar attempts in reproducing the master's works, respecting the «good rules of the art», also deals with a world ruled by the inertia and the resistance to every change, in favour of the permanence of what a long tradition has proved to be sure and good. In the mean time, nevertheless, the construction methods, materials and techniques have known indubitable changes during the past ages, due to individual contributions of single or of greater ensembles of workers, artisans, professionals, technicians, both casual or rationally searched, proposed and developed. Let us think, simply, to Filippo's Brunelleschi role, not only for the realisation of the Dome of «S. Maria del Fiore» in Florence, as a monument of the universal architectural history, but more over for the revolution of the construction methods between the ancient and the modern world.

It could be sufficient, to understand this continuous confrontation between sudden events and long lasting phenomena, or between tradition and innovation, paradigmatic or revolutionary periods within the past of the construction processes (using a concept deriving from the contemporary epistemology), to look at some images of ancient construction sites.

We can so select an image of the construction site of roman building, Figure 1, and then one representation of the «Babel Tower» under construction, one of the most ancient and symbolic images of the building activity, that lasted till the Gothic age, Figure 2. Then, we can look at the miniature of the Oxford Library representing the «Tempio Malatestiano» in Rimini, by Leon Battista Alberti under construction, figure 3, and finally a table of the Encyclopaedia, by Diderot and D'Alambert, devoted to the masonry works, figure 4. They are only few images selected as simple matter of discussion and we could choose other paintings, mosaics, miniatures or sketches indifferently belonging to the same centuries. What it is important to note, in any case, is that in all these images we can recognise almost the same actors, the same workers, instruments, gestures and behaviours.

It is always a scene, not only of costume but of work and production, that took place around some buildings that, even if with some differences, reflecting the changes of the forms, the styles, the uses determined by the passing time, show some deep and structural similarities.

These images seem to translate, in the visual language of evidence, what we tried to point out before.

Within the field of the constructions, in fact, seems existing a sort of uninterrupted continuity between

Figure 1
An ancient building under construction. Fresco of the *Ipogeo di Trebio Giusto.* Rome, IV century a.d.

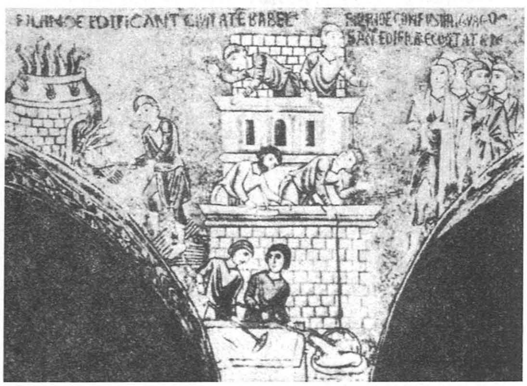

Figure 2
Mosaic with a building construction site (the Babel Tower), ca. 1135–1145 a.d. Palermo: Royal Palace, «Cappella Palatina»

the first periods, after the fall of the ancient world, and the most recent expressions of modernity. If we accord, of course, with the historic sciences that consider the modern age beginning with the discovery of the America and lasting till the contemporary age, passing through the fall of the powers of the «ancien regime», signed by the French Revolution.

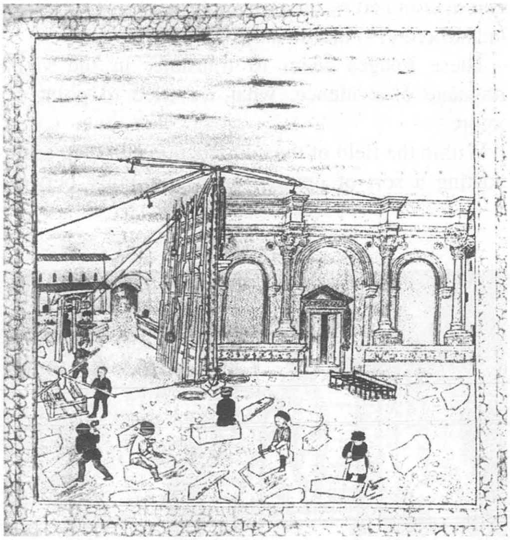

Figure 3
The «Tempio Malatestiano» under construction in a miniature by Giovanni da Fano. In Basilio, Hesperis, fol. 137r. —Oxford Boldleian Library

If we now choose, again as a simple occasion, a representation of the Crystal Palace by Joseph Paxton, under construction (1851), Figure 5, we can easily image how deep, even if not immediately generalised and effective, the changes occurred from the age of Diderot and D'Alambert where. It seems in fact that less than half a century had been sufficient to interrupt and completely abandon the world of references, knowledge, ideas and instruments that apparently ruled the constructions for more than a millennium.

The fact is that the contents of all these images, and of similar others, are in some way comparable and allow us to understand perhaps more than what conceive their denotative and immediate message. We can thus appreciate the changes occurred in the sense of duration of the portrayed architectures, in the kind of structures related to the effects of gravity or in the protection from the assaults of the climate and of the weather. We can also appreciate how the relationship with the site, the production processes, the organisation of professionals and workers, the

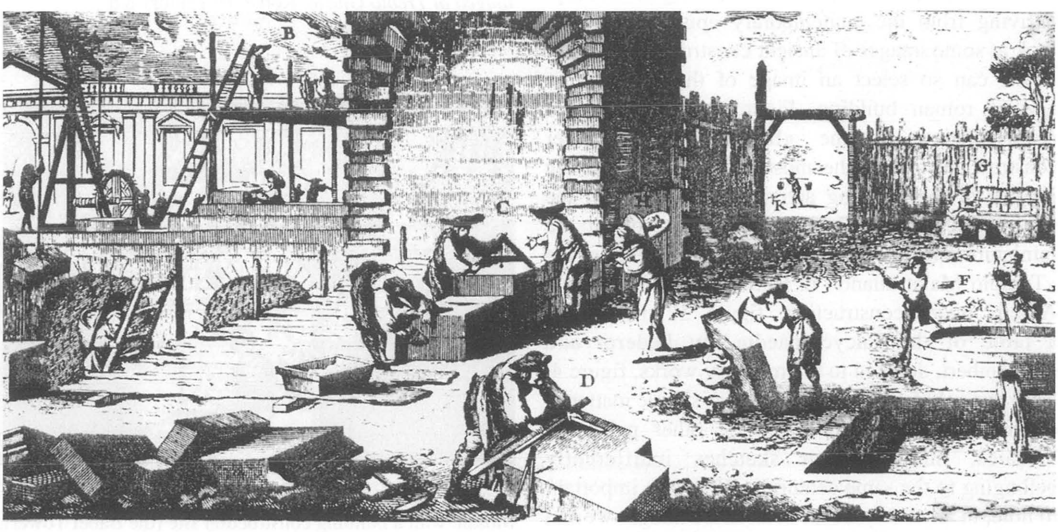

Figure 4
A representation of a construction site with a masonry structure. Diderot et D'Alambert, *Enciclopèdie,* Table n. 24

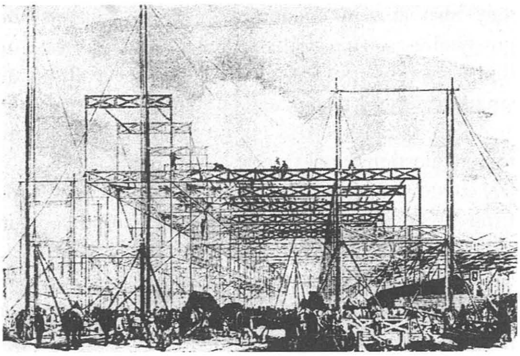

Figure 5
The Crystal Palace by Joseph Paxton under construction from the Illustrated London News —16/11/1850

role of the owners, and so on, deeply changed within the first and the last image. The awareness about the resistance and quality of materials and structures, belonging to an ancient empirical traditions, ensured by the prove of the time, suddenly seems to leave the place to new methods to choose, produce an put in site materials and constructive elements. In any case, starting from the Crystal Palace, another continuity begun, and we are now, in some way, direct heirs of that conception of the architecture while, perhaps, we are only far nephews of the ancient world that lives trough the others images.

So, once again, we are obliged to carefully consider and to use in a correct way all the references to events and to enduring processes not to give the prominence to any one of them. On the contrary, we could not correctly «write» any construction history but only separated monographs of single buildings or fantastic and «constructed histories» of a never existed past.

Is it possible a global construction history of the past?

This brings us to another fundamental question. Will it be really possible to enlighten all the past, knowing that we can only study some rests of the previous ages and that we do not exactly know what the ancient builders thought, what they knew and how they operated? Will it be achievable a complete construction history?.

The answer is, in same way, simple and it is negative, even only considering that any construction history in any case belongs to the general history and that the contemporary theoretical and methodological elaboration says us that a similar goal is really unachievable.

It is a long time since the historians have abandoned the illusions belonging to the first periods of the modern historical sciences, according to which the historian should only study the facts, nothing more than the facts. Ranke or Fustel de Coulanges proposed this rule, founding the new history of the states and of the policy, after the dynastic or diplomatic one that already had substituted the ancient myths. In any case, thanks to the work of others scholars like Block, Le Goff, Braudel, Furet, and Nora, we finally know that the facts are nothing more than a creation of the researchers themselves. We always select them from the great numbers of evidences, of traces, weak or strong, clear or confused, unique or ambiguous, rather than finding or recognising them as certain and indubitable facts.

We also know that we can make historical researches using different information sources, direct and indirect, ideal and material, not only studying the ancient buildings, but even the life of a community, like that of the medieval French village of Montaillou, exemplary studied by Le Roy Ladurie.

Not only the outstanding acts of great peoples, or of great architects, could be useful for understanding the past of a community or of a series of buildings. Also the facts of the common life of the community which they belonged to, can play a fundamental role, as those of the workers or builders of the examined architecture, even if we do not have any official registration of their individual existence and production.

We know, further on, that it is even possible to «make history» of the absences, or in absence of any clear and direct information about a certain phenomenon. This is; for example, the great lesson given us by the studies carried out within the building archaeology. Let us think, apropos, to the analysis based on the recurrence of forms, dimensions, materials or constructive techniques of single elements, such as openings or balustrades, within a geographical region, signed by homogeneous cultural, social or economic characters. This studies, that require the systematic work of different

researchers and sometimes of different disciplinary competencies, allow us to date a great number of buildings and to understand their past history, even where we do not have any documents, or when we do not know where we could start from.

For these reasons we know that a global and definitive construction history will never exist.

On the other hand, we can only examine the buildings received from the past, even not only them, hoping to construct, step by step, an history always open to the necessary revision of the acquired and provisional results. At any advancement of these attempt, in fact, we will be obliged to go back and, thanks to the knowledge achieved on a general level (that of the construction culture of a place, or of a period), to examine again some of the single buildings we started from.

This could only be the virtuous circle of any open and non-deterministic knowledge process that keeps together the individual and the general aspects of the construction adventure in the past ages. It is a virtuous circle that asks the co-operation of all the involved disciplines, because the constructions could obviously be studied from the specialised related points of view, but they could not be really understood only considering them.

Knowledge versus knowledge, or knowledge for practical needs

The philosopher Benedetto Croce, the father of the neo-idealistic thought in Italy, once polemically asked to himself which could ever be the interest, in our days, in enquiring the story of the Dodecanneso war. He simply answered none. He thus certainly affirmed his particular conception of history as the only possible philosophy and science. As it is well known, he thought that the only real and important facts are those belonging to the spiritual nature of men and this conviction also affects his evaluation of men's expressions, starting just from the art works. In any case, also forgetting this opposable opinion, there is something in that question that we can not simply ignore.

A part any other theoretical implication, in fact, we have to clarify if our attempts toward the discovery of the secrets of the ancient constructions are only devoted to enlarge our knowledge of the past, or if they also aim in conquering new instruments for practical uses. This could be, for example, the case of the needs of preservation, care, restoration or strengthening of the ancient structures.

Again, the problem is not obvious and the answer to this question is not free of consequences. Not only Benedetto Croce but, for example, Manfredo Tafuri, from e very different point of view, underlined the crucial role of this kind of problem. It is easy, in fact, to understand that, if we investigate a single building and if we use, for this purpose, the achievements of a general «Construction History» to choose, for example, what to preserve, change or restore, everything could begin very dangerous. The way in which we consider and develop all these different activities could be full of contradictions, conflicts and even destruction.

Any general and a-priori prominence given to our pragmatic needs could affect, in the mean time, both the research and the intervention. This is, with evidence, something we must certainly avoid. We always have to affirm and to respect the mutual independence of the two activity fields, that of the research carried out around and upon the ancient buildings, towards the construction history, and that of the intervention on the same buildings, especially decided for their care and preservation.

Only this situation could allow good results on both hands. This is particular true if we think to the great problem of the structural repairing or reinforcing of ancient damaged buildings, where we still have a lot of difficulties in understanding the logic of the behaviour that the ancient builders adopted and that the time and the occurred changes determined. The chronic of recent or less recent interventions easily offers several examples of what can occur to a monument when we impose it a new structural behaviour, without having previously understood how it was conceived, or simply thinking that our interpretation is the right one. With this kind of intervention, we often use in a non correct way the knowledge achieved in this field and, in the mean time, we deny any future chance to understand the real structural behaviour of the building and, moreover, we erase a sample for the future research possibilities.

So, every future research is welcome in this field but it should not be based only on pragmatic and casual demands.

In form of provisional conclusions

The few and weakly delineated observations till now proposed do not close in any way the problem of the expected and hoped inscription of any Construction History within the rigorous domain of the historic sciences. They only intended to propose some matter of reflection to this scientific community and underline the deep theoretical content of any our attempt in «writing» the future history of the past construction methods and techniques.

Finally let me say that I really do not believe that we could easily close this topic and subject within the borders of any our structured and formalised discipline. First of all, because they are in crisis in themselves, as a heritage of the XIX century that sometimes we consider immutable and perfected (in the Latin meaning of «concluded»). Secondarily because they show all the limits related to the period they were born in, and those accumulated in the past decades following certain direction of the research that, now, seem to be incapable to achieve new results. The only way that remains open is, therefore, that of a multidisciplinary work not intended as a simple accumulation of results achieved in the respective separate fields but as a real reciprocal contamination of ideas, methods and goals. There is no more sense in dividing the history of the sciences from that of the arts and we can not forget, in any case, the history of mentalities, of economic processes or that of educational systems. This right to remember some of the new directions of the recent development of the historical studies all over the world.

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A case study of thermal environment on the construction history of modern Asian architecture between Asian traditional house and European style

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Kenichi Hasegawa
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European colonialism occurred on a global scale and resulted in broad changes to the society of the affected country. In particular, changes to the religion, laws, and architecture were observed. When a country was colonized, many of the first buildings to be constructed followed the design and construction ideals of the colonial power. As the colonial power was usually based in significantly different climatic regions, many of these new buildings were unsuitable for the new country. With time therefore, these new design principles were modified to reflect the local environmental conditions and traditional architectural styles.

A large part of modern Asian architecture reflects this cultural evolution. In this study, we examine the change in the design of Indonesian housing by examination of the thermal environment of housing from different periods. In particular, we examine the effects of the addition of verandahs and the enlargement of roof spaces to the thermal comfort of the living space. Previous studies have examined the thermal environment of housing and a storehouse (Kimura, 1996). However, this paper examines the thermal environment with respect to the evolution of the design principles of the time.

A history of the study area and the selection of case studies

A number of factors were taken into consideration in the selection of geographic region and the actual houses. The primary factor was the identification of a former European colony. Other considerations included climatic conditions that are distinct to that of the colonial power as the architectural style initially adopted by the governing country usually mirrored that of the home nation, and the identification of areas that contain a mix of both colonial and native architectural styles.

The former Dutch colony of Indonesia was selected as a suitable study region. In particular, we examined the mountainous city of Bandung and Cirebon, which is situated on the coast. Cirebon is a small fishing village whose history can be traced back to beginning of 20th century. It became the harbor area of Bandung when Bandung became an important commercial centre.

In the early part of the 19th century, the VOC, the United East India Trading Company, was dissolved by the Dutch Government. A Governor General headed this remote administration as a representative of the Central Government. During the period 1808-1811, Governor General H.W. Daendels introduced policies to permit individual foreigners to buy large areas of land and the construction of the 1,000 km road from Anyer in the west to Panarukan in the east. This road was primarily designed for military defense purposes and was known as the Groote Postweg (the main transport road). The road gave rise to the construction of Bandung in 1810.

In the early years of the life of the city, the houses were built separately as opposed to large groups (F. Wieland, Hendrik and AgBraga, 1997). Following the

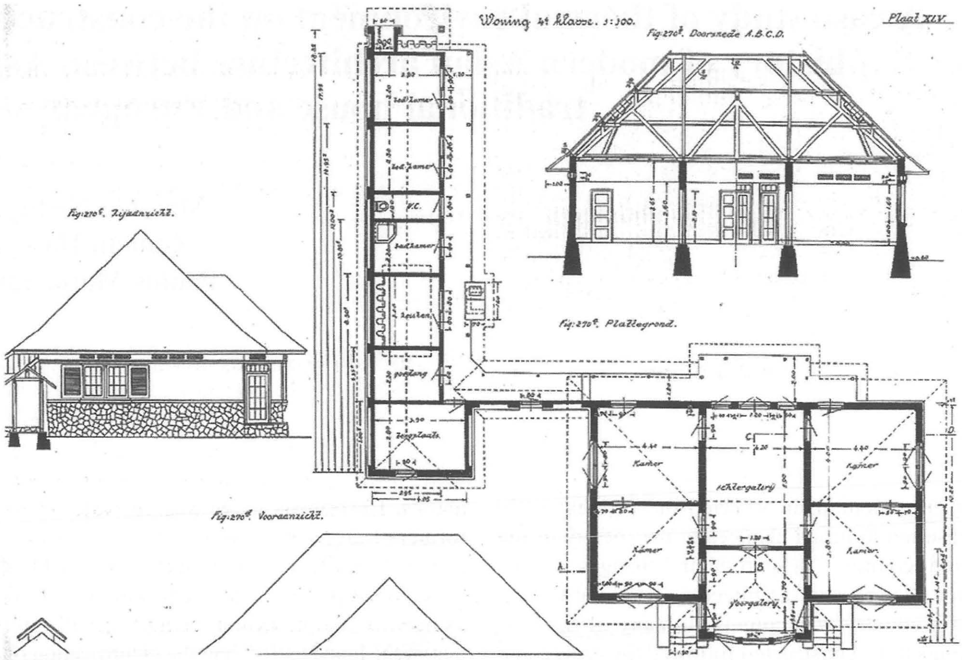

Figure 1
An example or early 20th century housing

plan of the transfer of capital of 1920, the framework of the current city was developed and the national government was moved to Bandung.

A collection of architectural styles (see Fig. 1) was published in 1927 (Pola 1927) and exerted a strong influence on the form of Indonesian housing. The book was published in Bandung and it is there that most of the examples of this style of construction can be seen. We chose the outskirts of the Cikapayang area of Bandung for investigation and in particular a middle class house dating back to the 1930's.

Climatic Conditions

Figure 2 show a climograph of three major Indonesian cities (Jakarta, Surabaya, Bandung) and Tokyo and Naha in Japan. Indonesia is located in an area having both wet and dry seasons. Therefore, the change in the monthly average temperature is small, but the change in relative humidity is significant. The altitude of Bandung means that the temperature is

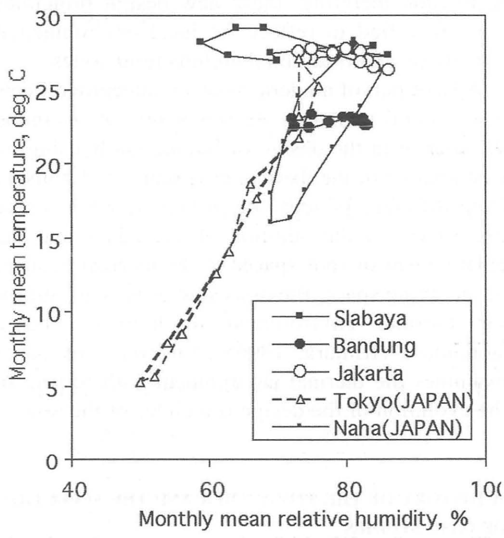

Figure 2
Comparison of climatic conditions of major Indonesian cities

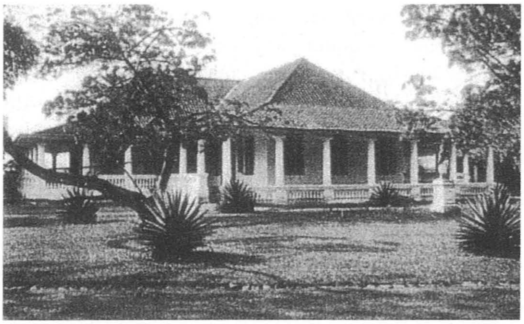

Figure 3
An example of a second period farm house

relatively low throughout the year. With regards to the relative humidity in Jakarta, the difference between the wet and dry seasons is smaller than that in Surabaya. The climate conditions in Cirebon are midway between Jakarta and Bandung.

Evolution of housing in Java

Three distinct architectural periods can be observed in the houses of Bandung. In the first period, which occurred in the latter half for the 18th century, the designers adopted a large roof with a European facade and a lengthwise window in the Dutch style (Sudradjat Iwan, 1991). In the 19th century, the second period saw the development of large farm houses. The closed facades were no longer used in favor of large verandahs. This design was still widely used in the 1930's, but no post-war examples can be found. In this report, we examine the second and third period housing.

The Selection of Houses

We selected 12 houses as shown in table 1. However, every examples of Cirebon are farmhouses that are now in the suburbs. CE2 corresponds to a house of the farm mentioned as followingd and the others are of the type usually occupied by junior clerks. They are small structures with a private room and verandah.

Investigation of Indoor Thermal Environment

Outline of Measurement Process

The temperature and relative humidity in each house were measured continuously at 10 minute epochs for

Table 1. An object house sign

BE1:	Cikapayang district, Bandung,	third period European house
BE2:	Prabudimuntu Bandung district	European house
BT1:	Lembang 1 Bandung Lembang district	traditional wooden house
BT2:	Lembang 2 Bandung Lembang district	traditional wooden house
BT3:	Atang House Bandung Lembang district	traditional wooden house
BT4:	Pasir Impun 1 Bandung Pasir Impun district	traditional wooden house
BT5:	Pasir Impun 2 Bandung Pasir Impun district	traditional wooden house
CE1:	Agus's House Cirebon / suburbs farm	second period European house
CE2:	Prayitno House Cirebon / suburbs farm	second period European house
CE3:	Suwaryo's House Cirebon / suburbs farm	second period European house
CT1:	Maman's House Cirebon / suburbs farm	second period traditional wooden house
CT2:	Suraji's House Cirebon / suburbs farm	second period traditional wooden house

10 days. The measurement points were located in the living room, bedroom, attic space, outside and so on. Measurements were recorded in the wet (November 1999 to February 2000) and dry (July to September 2000) seasons.

Indoor temperature profiles

Figure 4 shows temperatures of houses CT2 and CE2 in the dry season. The indoor temperature of CT2 was similar to the outside temperature whilst the fluctuation in the indoor temperature of CE2 was less significant. The highest temperature was between 2 and 3 °C lower than the outside temperature and the lowest nighttime temperature was 5 °C higher than the outside temperature. These results show that the thermal mass of the wall has a significant effect on indoor temperature as the use of brickwork in the European designs haslimited the indoor temperature changes. It also shows that nighttime ventilation is important

Tables 2 and 3 show an average living room temperature and humidity during the wet and dry seasons, respectively. Generally the average indoor

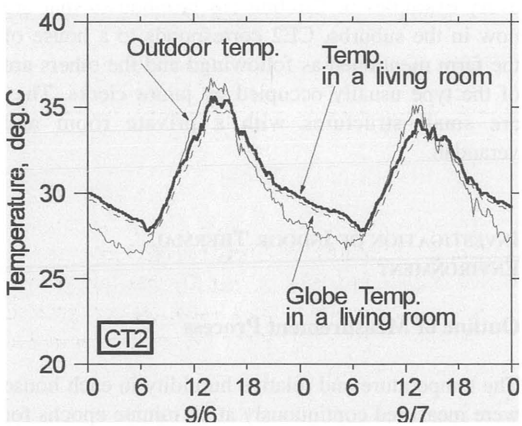

Figure 4
Fluctuation of indoor temperature and humidity of CT2 and CE2 in the dry season

Table 2. Daily average temperature and relative humidity in living rooms during the wet season

	Indoor temperature, deg. C			Relative temperature, %		Radiational Temp., drg. C	
	AVG.	SD.	Ratio of temp. swing	AVG.	SD.	AVG.	SD.
BE1: Cikapayang	27.1	0.8	3.1	61.9	7.3	26.6	0.8
BE2: Prabudimuntur	26.2	1.4	6.3	58.4	7.9	25.0	1.7
BT1: Lembang 1	20.2	2.3	10.2	75.2	6.5	19.8	2.3
BT2: Lembang 2	20.7	2.6	10.9	67.9	5.7	20.7	2.7
BT3: Atang House	23.3	3.5	13.8	—	—	23.3	3.5
BT4: Pasir Impun 1	24.0	3.0	11.5	62.9	9.6	24.1	3.1
BT5: Pasir Impun 2	25.3	3.7	15.7	61.3	10.9	25.4	3.8
CE1: Agus's House	29.8	1.4	6.7	58.2	7.3	29.8	1.3
CE2: Prayitno House	30.3	1.0	6.5	83.7	3.3	27.0	0.9
CE3: Suwaryo's House	29.5	1.2	6.1	59.3	7.1	—	—
CT1: Mamans House	30.8	2.2	9.1	55.8	9.1	30.8	2.2
CT2: Suraji's House	30.3	2.1	9.4	57.6	9.4	30.1	2.1

Table 3. Daily average temperature and relative humidity in living rooms during the dry season

	Indoor temperature, deg. C			Relative temperature, %		Radiational Temp., drg. C	
	AVG.	SD.	Ratio of temp. swing	AVG.	SD.	AVG.	SD.
BE1: Cikapayang	25.6	0.8	3.9	71.5	6.3	25.5	0.8
BE2: Prabudimuntur	24.2	1.1	6.8	77.6	8.0	24.1	1.0
BT1: Lembang 1	20.2	1.4	6.9	87.2	6.3	20.1	1.4
BT2: Lembang 2	19.7	2.0	9.8	85.3	8.7	19.6	2.1
BT3: Atang House	21.6	1.7	8.5	—	—	21.5	1.7
BT4: Pasir Impun 1	24.0	1.9	8.7	83.1	7.9	23.8	1.9
BT5: Pasir Impun 2	23.7	2.6	12.6	74.9	9.3	23.8	2.7
CE1: Agus's House	27.1	1.0	5.6	83.5	3.4	27.0	0.9
CE2: Prayitno House	28.2	0.8	5.8	78.7	3.0	27.9	0.8
CE3: Suwaryo's House	27.4	0.9	4.7	82.3	2.7	—	—
CT1: Mamans House	28.6	1.3	5.9	77.6	4.1	28.4	1.3
CT2: Suraji's House	27.8	1.3	6.0	81.3	4.4	27.7	1.3

temperature of the houses in Cirebon are higher than that in Bandung, although it is necessary to consider the difference of measurement period. The average indoor temperature in some houses in Bandung is as low as 20 °C. The difference in the daily average temperature between the traditional wooden and European houses is not apparent. In the wooden houses, which use light materials, the fluctuation in the indoor temperature is large. It is suggested that in the European houses, nighttime ventilation in combination with the thermal mass of the walls has a positive impact on cooling.

Relationship between ratio of temperature Change and daiLy mean temperature

Figure 5 shows the difference between the daily average indoor and outdoor temperature and the ratio of the daily indoor and outdoor average temperature (indoor temp. / outdoor temp.) for all houses. A small ratio of daily indoor and outdoor temperature and difference in daily average indoor and outdoor temperature are favorable in terms of comfort. European houses are constructed with brickwork, and hence the ratio of the daily indoor and outdoor temperatures were below 0.7. Conversely, with the traditional wooden houses, the ratio is always greater than 0.6. With regard to houses BE1 and BE2, the ratio is approximately 0.2. In the case of the European houses, the difference in the daily average indoor and outdoor temperatures were between –0.3 and 1.2 °C. The difference in CE2 (1.2 deg. C) was higher than the other European houses. It is therefore suggested that houses BE1 and BE2 have the most comfortable thermal environment.

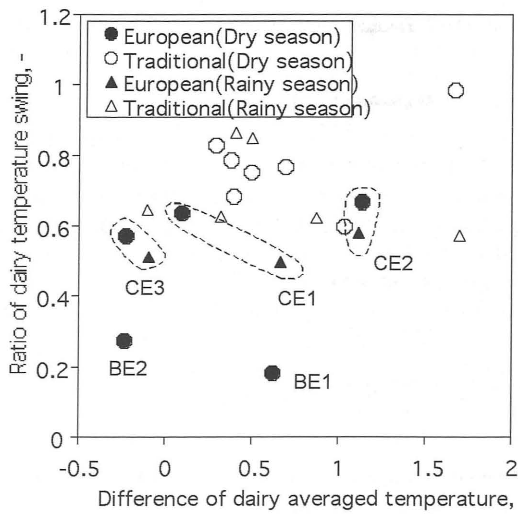

Figure 5
Overall distribution of temperature swing

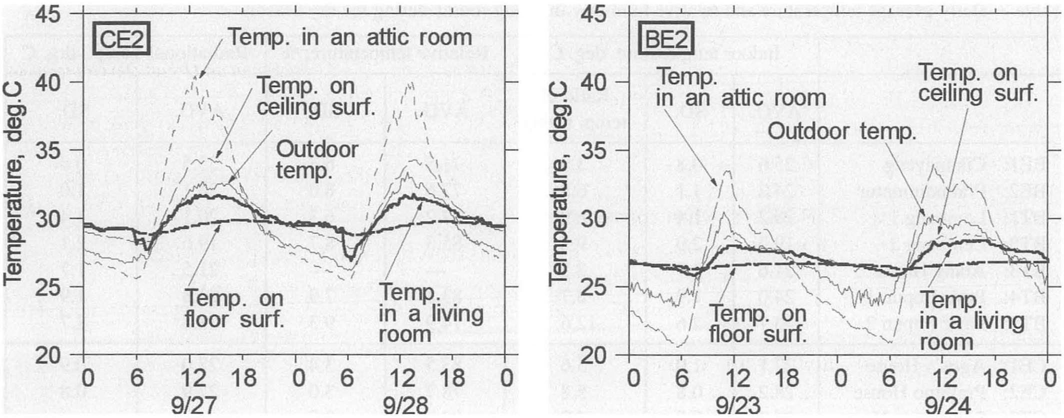

Figure 6
Indoor surface and attic room temperatures in CE2 and BE2 during dry season

Detailed temperature Results

Figure 6 shows the temperature in the attic space and ceiling surface temperature profiles of buildings CE2 and BE1. Fine weather was recorded during the measurement period at both houses. The attic space temperature in CE2 varied between 25 and 40 °C and was between 6 and 7 °C higher than the daytime outdoor temperature. The nighttime temperature was equal to the outdoor temperature. Conversely, the attic space temperature in BE2 was 3 to 4 °C higher than the daytime outdoor temperature 3 to 4 °C lower than the nighttime outdoor temperature. This difference may be affected by solar radiation, but the attic space temperature in CE2 rises more steeply than that in BE2. As the roof materials of both houses are the same, it is suggested that this difference is caused by roof shape. Furthermore, the attic space temperature affects ceiling surface temperature. The surface temperature of the ceiling in BE2 was lower than the daytime outside temperature, but that in CE2 was higher. This difference in surface temperature will have a significant effect on the indoor thermal environment of the living room.

Consideration of evolution of house form by measurement results

The results from the houses in Cirebon show that high daytime temperature rises were moderated by the brick construction. Among the measurement examples of Bandung, a form of BE1 and BE2 was the ones which let it miniaturized and transform CE2, but no significant difference in indoor temperature was observed. However, it has been shown that cabin temperature is a function of roof shape.

With respect to the large farm house (CE2) and the junior clerk houses (CE1, CE3) in Cirebon, no evidence was found to suggest that simplification to depend on a change of miniaturization and assigning rooms was always successful from the thermal environmental side. Furthermore, in a housing plan of a city, it is expected that a more positive device was needed. Enlargement of the attic space regarded as the example which let it reflect a change on such a method of construction. This was shown by the measurement of the ceiling temperature.

Conclusions and recommendations for future research

In this study, we examined the design and evolution of housing in a former European colony by examination of the thermal environment in existing structures. Examples from each period of construction history were identified and environmental data recorded on a continual basis during both the wet and dry seasons. The relationship between building technology, design evolution and indoor thermal environment were

considered and it was shown that the change in roof shape was the primary factor in the improvement in living conditions.

This project forms a case study of both architectural history and environmental engineering. It is important to preserve the older architectures in society as they help to provide a description of the historical conditions of the region. However, when considering the protection of the environment and conservation of natural resources, it is necessary to accumulate a more efficient building stock. Therefore, construction technologies have to be reevaluated.

This study will continue with a more detailed survey of the housing in the region and the inclusion of data from other areas of Asia.

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Eduardo Torroja and «*Cerámica Armada*»

John Ochsendorf
Joaquín Antuña

The Spanish engineer Eduardo Torroja Miret (1889–1961) was one of the leading structural designers of the 20th century. Torroja's extraordinary work includes two of the most significant thin shells in reinforced concrete: the market hall of Algeciras (1933) and the roof of the Zarzuela Hippodrome in Madrid (1935). (Fernández and Navarro 1999; Billington 1985) Though Torroja is better known for his work in thin shells of reinforced concrete, he pioneered numerous ideas in construction during his long career. One of his most significant ideas, construction in reinforced brick, or *cerámica armada*, has not received significant attention from historians of construction.

This paper examines Torroja's use of reinforced brick as a construction system. Following on the long tradition of timbrel vault construction in Spain, Torroja developed a system of thin brick shells, lightly reinforced with steel bars to resist tension. The fundamental advantage of the proposed system was the possibility to build shell structures without any supporting formwork, except for lightweight guides for the placement of the masonry. Thus, Torroja's use of reinforced brick provided an inexpensive and efficient structural system, which reduced the formwork costs associated with complex forms in reinforced concrete. Torroja applied reinforced brick throughout his career, from his earliest work on bridge caissons in the 1920's to a series of mountain churches in the 1950's. This paper provides an overview of Torroja's work in reinforced brick and the construction process he developed.

Historical Development of «*Cerámica Armada*»

Torroja did not invent the concept of metal reinforcing in brick. In the late 19th century the French engineer Paul Cottancin patented a system of reinforced masonry and concrete, which he called *ciment armé*, in contrast to Hennebique's *béton armé*.[1] Most notably, the architect Anatole de Baudot applied Cottancin's system in the church of St.-Jean de Montmartre in Paris completed in 1904. (Frampton 1995) Around the same time, Rafael Guastavino, Jr., son of a Catalan master builder who immigrated to the United States, was granted a patent for reinforced brick shells as shown in Figure 1.[2] (Collins 1968; Huerta 2001) It is likely that Torroja was aware of these systems though they do not appear to have inspired his own work on reinforced brick.

The Uruguayan engineer Eladio Dieste was the most accomplished designer in reinforced brick of the 20th century and his work has been well documented in recent years. (Jiménez 2001; Pedreschi 2000) Dieste began his experimentation in 1946 and was responsible for hundreds of innovative long span buildings in South America over the next 50 years. It is clear that *cerámica armada* was an independent invention in South America. Dieste was not aware of the reinforced brick precedents in Europe and he distanced his system from timbrel vault construction. (Tomlow 2001; Ochsendorf 2003) Conversely, Dieste's work may have stimulated Torroja to revisit the concept of

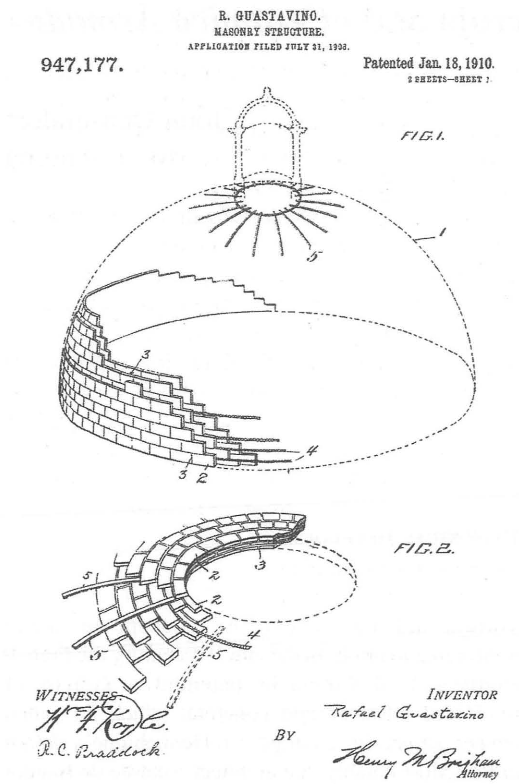

Figure 1
Patent for reinforced brick shells issued to Rafael Guastavino, Jr. in 1910. (Source: U.S. Patent Office)

reinforced brick construction in the 1950's. Although there is no proof of any correspondence between Torroja and Dieste, it is possible that Torroja learned of the early work by Dieste during a trip to South America in the summer of 1952. Torroja traveled widely in Argentina, Chile, Colombia and Peru, giving dozens of lectures and meeting with leading South American engineers. In his first application of *cerámica armada*, Dieste completed the thin brick roof of Casa Berlingieri in 1947. Dieste published this project in a South American engineering journal, so the work was known in the construction community and it is likely that Torroja would have learned of Dieste's work during his travels. Upon returning to Spain, Torroja completed a flurry of small church projects in the next several years and he dedicated himself to structural design in reinforced brick during 1952 and 1953. (Antuña 2002) Torroja's design proposals were based on his earlier experience with reinforced brick shells, which began with the foundations for the Sancti Petri Bridge in 1926.

Sancti Petri Bridge Caissons (1926)

In 1923, Torroja began his career in the company Hidrocivil, working for his former professor, the leading engineer José Eugenio Ribera. Among other projects in his early career, Torroja designed various foundation systems for bridge piers and in 1925 he proposed a new system for the caissons of the Sancti Petri Bridge in Cádiz, Spain. This system was composed of two brick shells, circular in plan, with an interior space that could be filled with concrete. The exterior and the interior walls had the form of concentric hyperboloids of revolution with a common vertical axis. (Figure 2) The surface of the brick vaults was then covered with a steel mesh on both sides together with a layer of cement mortar to reinforce the caisson. The exterior dimensions were approximately 7 meters in diameter and 6 meters high and the thickness of the brick walls was about 8 cm. The interior cavity between the two walls was then filled with concrete to sink the caisson and provide a foundation for the bridge superstructure.

The brick vaults were constructed with a double layer of hollow tiles, called *rasillas* in Spain. This

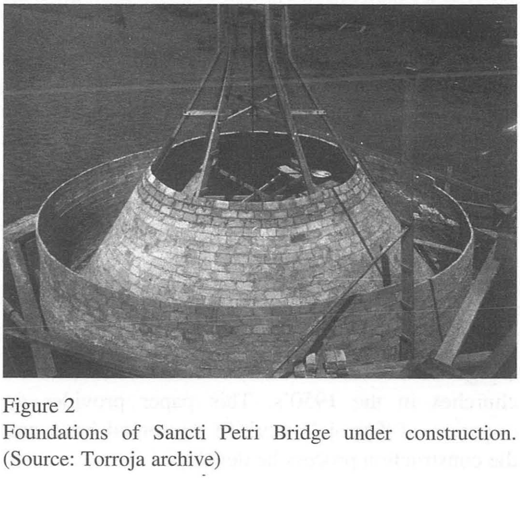

Figure 2
Foundations of Sancti Petri Bridge under construction. (Source: Torroja archive)

thin vault, known as a timbrel vault or *bóveda tabicada*, remains a common structural system in Spain and is valued for its ease of construction. With a fast-setting mortar, these vaults can be built without formwork or other temporary support.[3] Torroja was a great admirer of traditional timbrel vaulting and he realized that it could serve as a permanent formwork for reinforced concrete construction. (Fernández and Navarro 1999) By constructing a shell of brick and pouring concrete on the interior, the brick becomes the exposed surface of the concrete. Thus, in the bridge foundations of Sancti Petri, Torroja married a vernacular tradition with his civil engineering education in reinforced concrete.

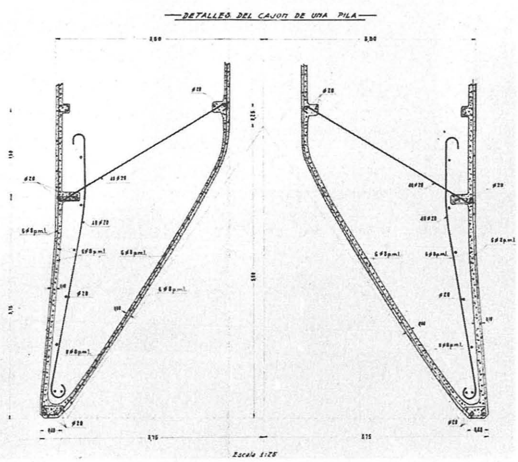

Figure 3
Sancti Petri bridge caissons under construction, with brick being assembled after the steel reinforcing cage is in place. (Source: Torroja archive)

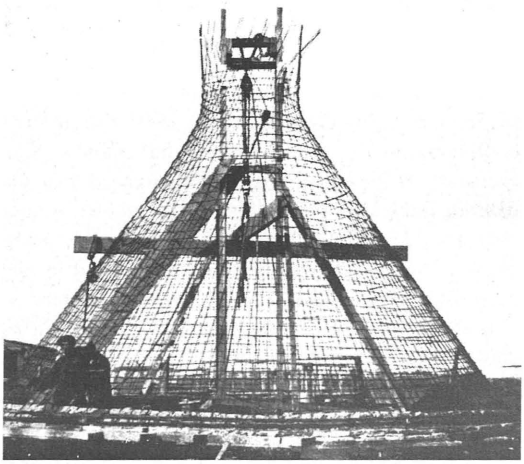

Figure 4
Brick shells together with steel reinforcing during construction of the Sancti Petri bridge caissons. (Source: Torroja archive)

Torroja seems to have refined the construction process for the Sancti Petri caissons as the project progressed. Figure 2 is clearly an unreinforced brick shell, suggesting that the vaulting was constructed first and the reinforcing was added afterwards. Figure 3 illustrates a completed reinforcing cage, which awaited the thin brick shells. Finally, in Figure 4 the vaulting is visible together with the reinforcing bars in a nearly completed caisson. It is not clear which system Torroja preferred and for what reasons, an issue which we will address in the discussion.

THE ZARZUELA HIPPODROME RESERVOIR (1941)

The reservoir tower at the Zarzuela Hippodrome in Madrid is Torroja's second significant work in reinforced brick. For the original project in 1934, Torroja proposed a highly innovative reinforced concrete structure, which would have required a complex formwork system. (Figure 5) Due to its higher cost the original design was never built and Torroja complained that the Spanish civil war «frustrated this dream as it did so many others.»

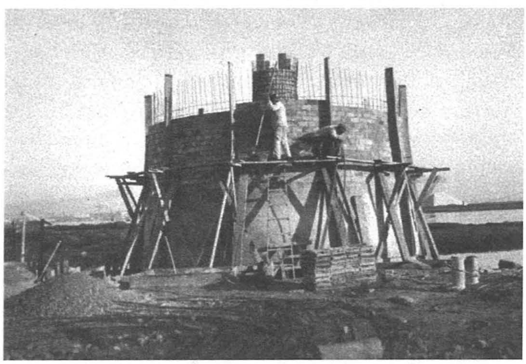

Figure 5
Torroja's original 1936 proposal for a reinforced concrete reservoir tower at the Zarzuela Hippodrome in Madrid. (Source: Torroja archive)

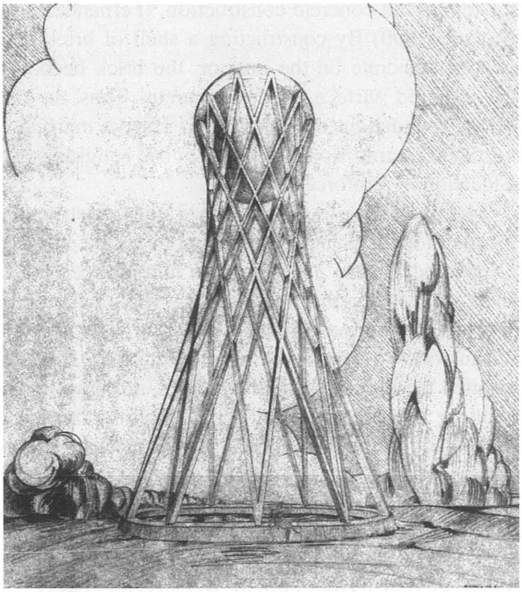

Figure 6
View of brick reservoir at the Zarzuela Hippodrome, Madrid. (Source: Torroja archive)

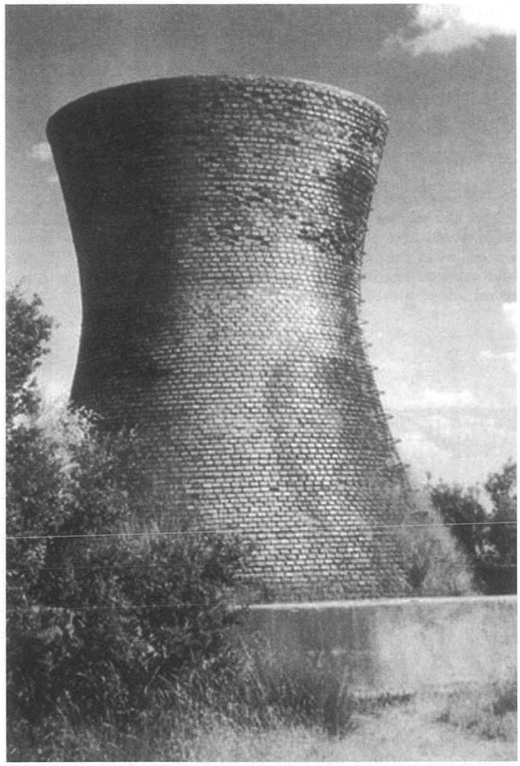

Figure 7
Cross-section of Zarzuela reservoir. (Source: Torroja archive)

(Torroja 2000) After the war Torroja constructed a reinforced brick tower which solved the same design problem at a substantially lower cost. (Figure 6)

Torroja's solution in brick is a hyperboloid of revolution, which in appearance is a precursor to the hyperbolic paraboloid cooling towers of reinforced concrete in later decades. The tower is elegant and simple, designed so that the lower region of unreinforced brick acts in compression. The upper region of the tower is subjected to internal water pressure and requires steel reinforcing to resist the resulting tensile hoop stresses. (Figures 7 and 8) The weight of the water is supported by a shallow concrete dome, which transfers the vertical load to the brick walls. The thrust of the shallow dome is redirected onto the walls with the aid of a tension ring at the base of the dome.

As with the foundations of the Sancti Petri Bridge, the method of construction for the reservoir is not clear. The key question in both cases is whether the steel reinforcing bars were placed prior to the brick, or after the brick was built. Because of the outward curvature at the top of the reservoir tower, the structure would experience tensile hoop stresses in this region during construction as well as in its final configuration. Figure 7 illustrates the extent of this curvature in the upper region and suggests that the exterior brick shell could stand under its own weight without steel reinforcing. The small tensile hoop stresses due to self-weight could be resisted by the cohesion of the brick and mortar assembly. Considering this possibility, it is likely that the brick shell was constructed initially and the steel reinforcing cage was installed afterwards. The concrete was then cast on the interior of the upper region of the tower. Though Figure 8 does not illustrate a masonry dome below the concrete shell, it is possible that this may have been constructed as a timbrel vault to serve as permanent formwork for the concrete dome. The shallow dome supporting the

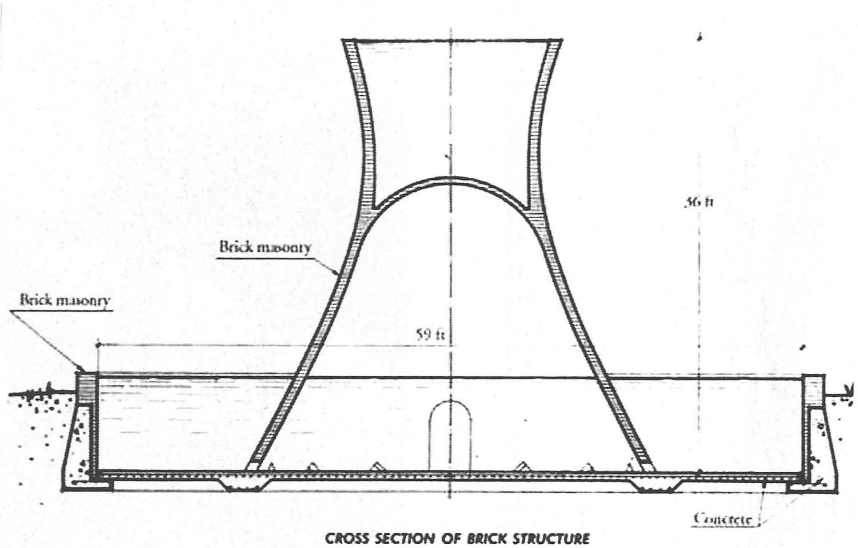

Figure 8
Drawing of reinforcing detail for the Zarzuela reservoir. (Source: Torroja archive)

water would act predominantly in compression under its own weight, and therefore could have been built as a brick or tile dome.

The Church of Pont du Suert (1952)

By 1950, Torroja was known internationally and had recently designed various systems of reinforced concrete shells for long-span roofs, such as the central hall of ENASA of 1948 and the roof for the experimental laboratory for the Instituto Técnico de la Construcción. (Antuña 2002) Upon returning from South America in 1952, Eduardo Torroja started work on several church projects in the Pyrenees Mountains. These projects, the churches of Xerallo, Pont de Suert, and the mountain refuge of Sancti Spirit, have been ignored, if not discounted, by historians and critics unimpressed by their formal qualities.[4] We will focus on the largest and most significant of these projects, the church of Pont du Suert in Llérida. (Figures 9–15)

The church of Pont de Suert has four parts: a long nave, terminating in an apse, with a small chapel and another room connected on the side. The reinforced concrete floor structure spans between masonry walls of 1.38 m thickness. The low masonry walls support the roof structure, which is a curving shell of lightly reinforced brick. The roof shells were built with minimal formwork and are of greatest interest to the present discussion. Each shell is made of two to three layers of thin bricks (*rasillas*), covered on the exterior with 3 cm of mortar reinforced with a 4 mm steel mesh. In each one of the four parts the form of the roof is different, but the construction technique is the same throughout.

A study of the structure of the nave serves to illustrate the constructive system. The exterior of the nave is a rectangular plan 13 m wide and 20 m long, plus 8.5 m of the apse and 2.5 of the low entrance to the choir. The lateral walls are of stone masonry 2.75 m high, measured from the plane of the interior floor, and 1.35 m wide, including an exterior façade of one layer of cut stone. The top surface of the walls forms a continuous plane to support the roof. For the interior face, the mass of the wall is decreased by repeating ellipsoidal niches 3 m wide. The roof of the nave is divided into five independent sections, called «lobes»

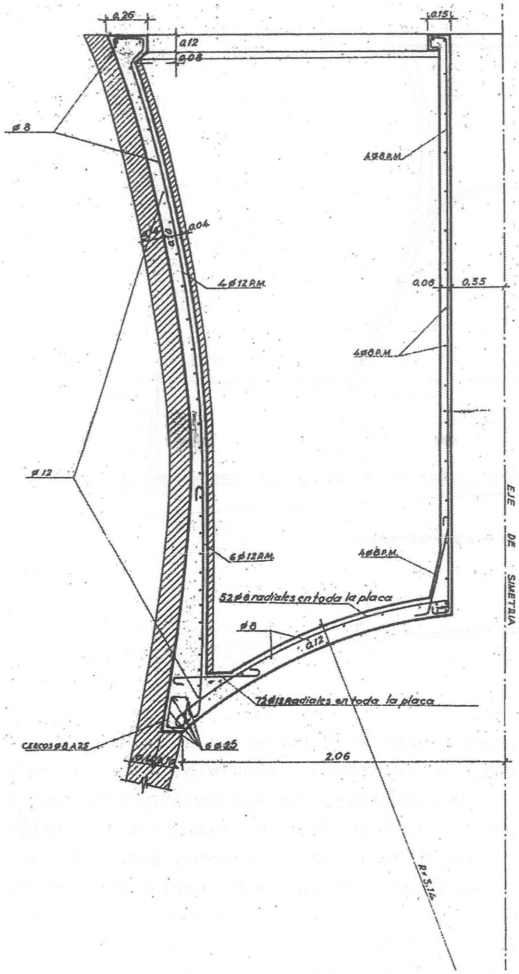

Figure 9
Church of Pont du Suert, Spain, 1952 (Source: *Informes* 1962)

by Torroja, which coincide with the ellipsoidal segments carved into the vertical walls. Two lobes lean out over the nave to form a pointed arch, supported at the base by the lateral walls. The transverse section of each lobe has the form of a circular segment with a variable radius, increasing from the support to the crown, to produce surfaces of double curvature. The interior span at the support is 12 m and the rise of the arches from the support to the highest point of the interior surface at the crown is 8.45 m.

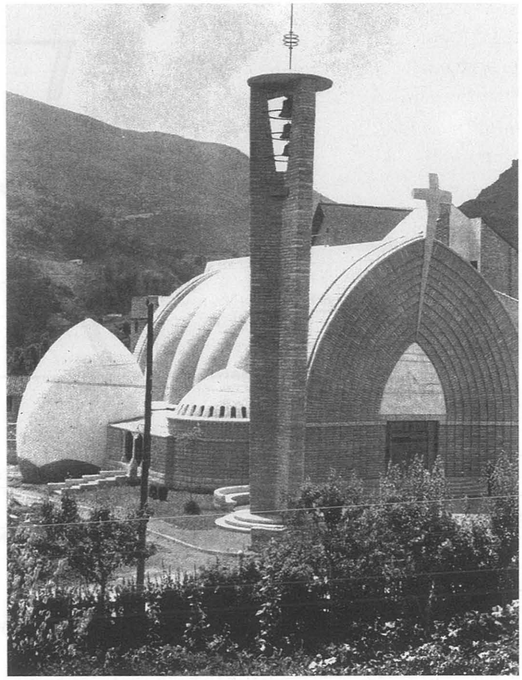

Figure 10
Floor plan of the church of Pont du Suert. (Source: Torroja archive)

The geometry of the shell surface is defined in a precise form, based on the construction method. It is a complex form which cannot be described by a simple analytical expression, but can be defined by a

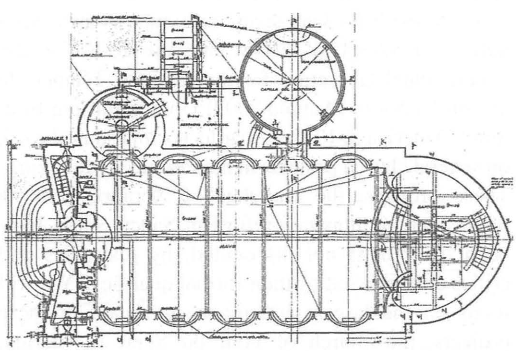

Figure 11
Cross-section of the church of Pont du Suert, looking down the nave. (Source: Torroja archive)

series of transverse sections. During construction, a thin metal framework served as a guide for the placement of the first layer of the thin bricks. The surface can be generated by displacing a curve of a circular segment from another similar curve with a different radius C_e. (Figures 12 and 13). The interior surface of the resulting figure is an arc segment of circumference C_i. The curves generated are contained in a horizontal plane which rotates on an axis passing through the center of the curve C_i. The surface is defined by the coordinates of 26 transverse sections contained within the plane and supporting points of the exterior curve of the lobe, as indicated in the figure. The lines that define the edges of the shell are curves whose transverse projection is the curve C_i, and in the longitudinal plane it is a curve corresponding to the expression:

$$y = 0{,}59x^{1{,}249} \qquad (1)$$

The curve is defined by the condition that its vertical asymptote is perpendicular to the ellipsoidal section of the lower niche. Figure 12 indicates the center of gravity of each curving section defined by the surface C_g, and the centroid of each of the arches, C_c.

To construct the roof, 26 guides were used following the form defined by the 26 arc segments indicated in Figures 13 and 14. The guides were placed on lightweight scaffolding, used to define the form of the first layer of the bricks, which would become the lobe. The first layer was placed with a fast-setting gypsum mortar and subsequent layers were built with a cementitious mortar in the same manner as the timbrel vaulting constructed by Rafael Guastavino. (Huerta 2001) The metal guides also helped to support the weight of the roof until the two sides of the pointed arch met at the crown. After the two sides were joined, the structure was stable and worked in compression predominately. A longitudinal beam at the crown of the arches connects all of the lobes along the exterior surface, without being visible on the interior. This provides a point load at the crown of the arch which causes the internal line of thrust in the roof to more closely follow the center of gravity of the section, reducing the eccentricity and any associated bending stresses in the brick shell. (Figure 15)

To analyze the structure Torroja treated it as a fixed-end arch with a hinge at the crown, which is a structure with two degrees of static indeterminacy. Torroja carried out an elastic analysis, considering the material as isotropic, homogeneous and perfectly elastic. He determined the geometrical characteristics of the various sections, area and moment of inertia, and with these values he calculated the internal stresses in the brick roof. Finally, he applied the same procedure to the roofs of the apse and the baptistery. The thrust of the nave is resisted by the lightly reinforced concrete walls formed on each side of the niches in the walls. The shell works in compression

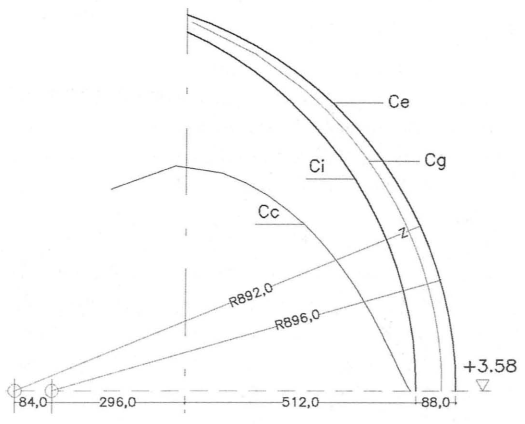

Figure 12
Geometry of the «lobe» for the church of Pont du Suert. (Source: Antuña 2002)

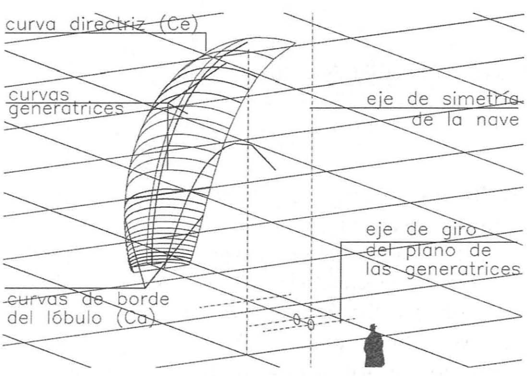

Figure 13
Three-dimensional drawing of an individual lobe. (Source: Antuña 2002)

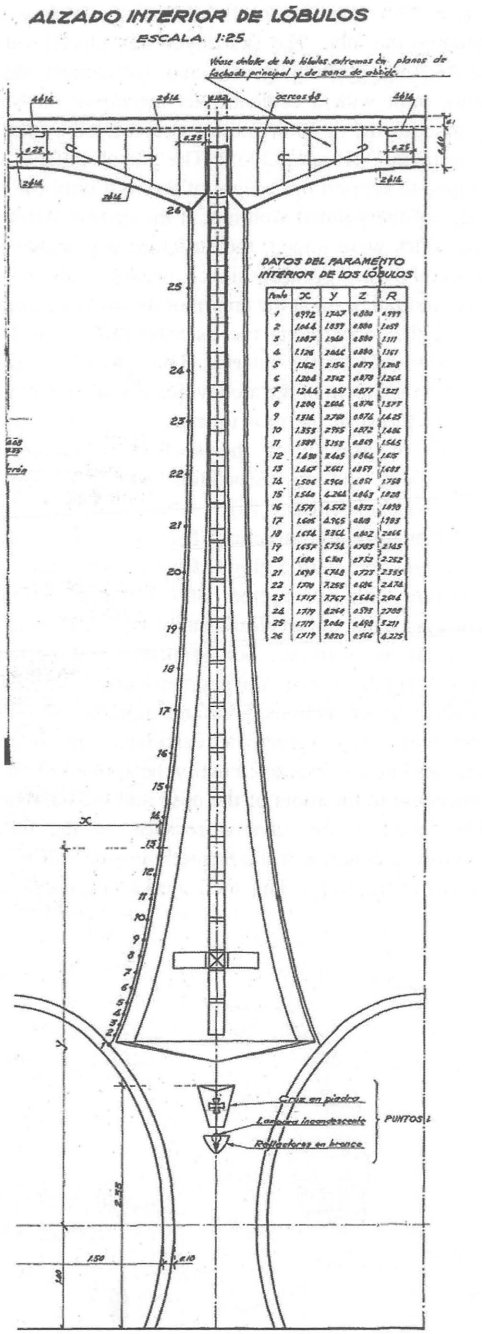

Figure 14
Elevation of the intersection between two lobes, including a table giving the geometry. (Source: Torroja archive)

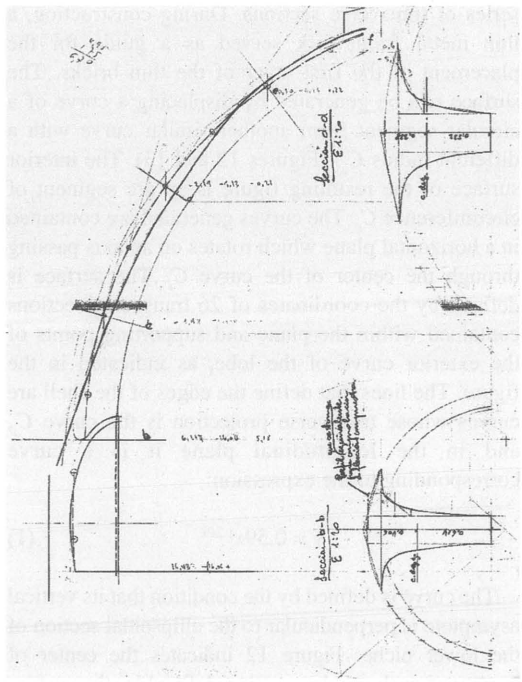

Figure 15
Graphic calculation of the internal line of compression acting in the arch of the church of Pont du Suert under self-weight. (Source: Torroja archive)

predominantly, using a thickness of 17 cm, so that the slenderness ratio is 70. The form of the structure is designed to be maintained in compression and the internal steel reinforcing is kept to a minimum.

In his earlier projects of reinforced concrete shells, Torroja used surfaces of a simple geometry: spherical domes, cylindrical shells, or ellipses. He imposed this limitation because it allowed him to make an elastic analysis of the structure by integrating the equilibrium equations, which had only been established for simple geometries. However, beginning with the church of Pont du Suert, he proposed more complex forms culminating with the roof of the club Tachira de Caracas of 1957. In the church designs, the small span and slenderness of the shell provided a stable surface of double curvature with very low stresses in the material. (At the shell support for the nave of the church of Pont du Suert, the compressive stresses in the concrete are

approximately 2.75 kg/cm^2.) The design for the church of Pont du Suert is the result of a detailed study of the adequate form for a brick vaulted structure which could be constructed with minimal formwork.

Discussion

In each of these three projects, Torroja chose reinforced brick for its advantages during construction. By using thin bricks, Torroja achieved complex geometries which would have been difficult to build in reinforced concrete. In particular, the formwork costs associated with reinforced concrete would have been prohibitive. Thus, Torroja's method of construction in reinforced brick is distinguished by one important characteristic: formwork is not required to define the curving brick surface. In each project, Torroja demonstrated the formal possibilities of reinforced brick as a construction system.

During his career, Torroja experimented with methods for combining the brick with the steel reinforcing. In particular, it is clear that he used different methods of constructing the caissons for the Sancti Petri Bridge, in some cases installing the steel prior to the brickwork and in other cases installing the steel after the brick.

Significantly, the Sancti Petri caissons and the Zarzuela reservoir were not mentioned in the commemorative journal issue published by the Torroja Institute after his death. (*Informes* 1962) This suggests that contemporary engineers did not attach much importance to Torroja's system of reinforced brick construction. Most engineers of the period did not think of reinforced brick as a viable system for large-scale structural problems, perhaps because they viewed brick as an antiquated material when compared to «modern» reinforced concrete.[5] Yet, these early projects in reinforced brick were clearly important to Torroja, for he included both projects in a book describing his best work. In the preface of the book (originally published in 1958) he wrote: «Many of my works are not mentioned here, but I feel that the few which are included best exemplify what I was searching for, and what I finally achieved.» (Torroja 2000)

Given the recent interest in reinforced brick structures designed by Eladio Dieste, it is worthwhile to compare and contrast the methods of *cerámica armada* developed by each engineer. Torroja and Dieste proposed two different solutions in *cerámica armada*, at approximately the same point in history, with the aim of reducing the construction cost for long span roof systems. The system developed by each engineer had various aspects in common:

a) In both cases, the structures have a form which is difficult to express analytically, but can be built easily due to the nature of brick construction.
b) Both engineers considered the structures to be formed by homogeneous and isotropic materials and they both made elastic analyses of their structures.
c) The shells are formed by modular elements, which can be repeated indefinitely, and can be built by reusing the same scaffolding and formwork.

However, the systems of reinforced brick designed by Torroja and Dieste are significantly different:

a) In the architectural design of the church of Pont du Suert, Torroja chose to finish the brick on the interior and exterior with a layer of mortar and paint. Dieste left his brickwork exposed in most of his completed designs. Though Dieste's method was less expensive, Torroja was concerned about the long-term durability in the harsh environment of the Pyrenees and his protective layer of mortar and paint is justified.
b) Though both Dieste and Torroja innovated in *cerámica armada*, their construction systems were completely different. Dieste proposed structures similar to thin shells of reinforced concrete that could only be built on a continuous formwork. In Dieste's structures, large tension forces are resisted by extensive steel reinforcing. Torroja's structures are closer to the tradition of timbrel vaulting, in which the brick is in a state of compression. Torroja explored forms which could be maintained in compression, with only small values of tension carried by minimal steel reinforcing.

Both Torroja and Dieste proposed solutions in *cerámica armada* as an alternative to the dominant system of reinforced concrete construction, though

few engineers have pursued this idea in recent years. Unlike Dieste, Torroja's proposals have not been further explored by engineers or historians of construction since his death in 1961.

Conclusion

By the 1950's, the construction of thin concrete shells was an expensive solution due to the increased costs of formwork and labor. Before steel construction became the most common structural solution for long spans, Torroja and others studied alternatives to reinforced concrete, which would not require expensive formwork systems. The construction aspects of these projects are of historical interest because they offer alternatives for an economical construction method using local materials.

Torroja's experimentation with reinforced brick was the result of his civil engineering education combined with his knowledge of the vernacular tradition of tile vault construction in Spain. The work of Torroja and Dieste suggests that brick is a useful material for structural design and construction, though these possibilities are largely unexplored in structural engineering today.

Notes

1. Cottancin received a patent in France in 1890 and in Spain in 1891. His Spanish patent, No. 12301, was titled «objects of plastic material, with metallic reinforcing, composed of a wire or other mesh» (*Objetos de materia plástica con armazón metálica compuesta de tejidos de alambre u otros*). A Spanish competitor, Antonio Macia Llusa received a patent in 1894 (No. 15562) titled «A system of construction by means of reinforcing formed of steel wire mesh, combined with various layers of brick or hollow tiles, covered with mortar or a layer of concrete» (*un sistema de construcción por medio de armazones formados por mallas de alambres de acero, . . . , combinadas con varias capas de ladrillos o rasillas . . . , enluciendo o no la obra con mortero o una capa de hormigón*). Several water reservoirs were built in this system at the end of the 19^{th} century in Spain.
2. It seems that Rafael Guastavino Jr. employed metallic reinforcing in some of his brick shell structures in the United States, though more research is required to document the extent of this practice.
3. This is the same construction system that the Guastavino father and son employed with wide success in the United States. (Huerta 2001)
4. One critic wrote that these mountain churches were «among the most ridiculous monstrosities in modern Spanish architecture.» (Fernández and Navarro 1999)
5. This situation is reminiscent of what historian Eric Schatzberg (1998) has termed the «progress ideology» of metal, when engineers neglected the advantages of wood as a structural material for airplanes during the 1930's and 1940's, choosing metal instead.

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Reinforcing foundations with wood piles: Origin and historic development

Mário Mendonça de Oliveira
Erundino Pousada Presa

It is an almost universally accepted fact that the earliest known references to architecture and building construction are found in Vitruvius' *Architectura Decem Libri.* As far as the use of piles to compensate for the low level of soil resistance, the famous author stated:

> But if a solid foundation is not found, and the site is loose earth right down, or marshy, then it is to be excavated and cleared and re-made with piles of alder[1] or of olive or charred oak, and the piles are to be driven close together by machinery, and the intervals between are to be filled with charcoal (Vitruvius, trans. Granger 1962, 1: 181).

Although this is all Vitruvius stated about the use of piles to solidify foundations, interesting conclusions can be inferred from his statement:

- Piles were driven close together to increase resistance;
- they were driven by machinery;
- hey were made of alder *(Alnus incana or Alnus glutinosa)*, olive *(Olea europea)*, or oak *(Quercus petraea)*;
- they were slightly burnt to increase their endurance (a well-known process to many who live in rural zones in Brazil).

One of the most distinguished translators of Vitruvius' work —16th century architect Claude Perrault— added a note to the text quoted above (Vitruvio, trans. Perrault 1684, 85). Perrault explained that according to Philander and Baldo, there were two types of machinery used to drive the piles close together: a large type moved by capstans, cables, and pulleys, and a smaller one that consisted of a manual beater in a tee shape to be operated by two people. Perrault also noted that the piles were not effective in swampy ground and an orthogonal reticular structure was used instead. It was made of resistant wood and the small squares were filled with small rocks on which the foundation rested, Figure 3.

Vitruvius mentioned elsewhere in his work that foundations supported by piles were used in the city of Ravena, Italy. This city was a port and its ground was known to be extremely marshy. Thus, foundations supported by piles must have been common at the time of the great architect. He probably observed the use of this technique by the Julius Caesar's legions he served. In *De Bello Gallico* Caesar mentioned the use of piles in the construction of bridges and other structures.

Archeological testimonies confirmed that Roman builders used piles to solve the problem of low resistance soil. The perforating end of the pile was reinforced with iron while the other end was reinforced with a ring to avoid fissures under the hit of the machinery. This technique survived all the way to our times.

From Medieval times only archaeology informs us about the use of wood piles in construction since construction techniques were not discussed by members of the *loggias,* but Venice is an example of

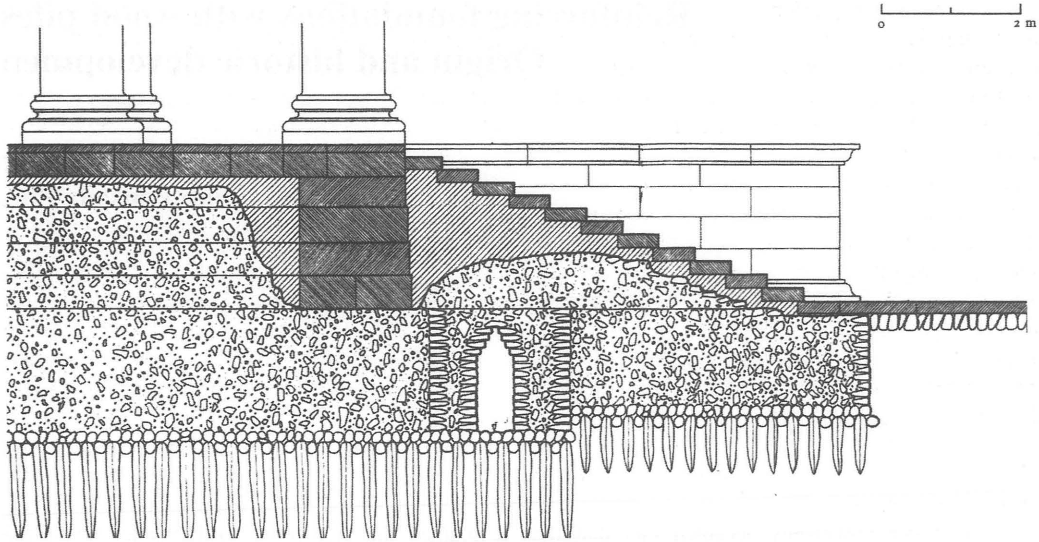

Figure 1
A foundation on piles supports the podium of the temple known as «Cicognier» in Aventicum. (Vitruvio, trad. Corso e Romano 1997, 1: 324)

the large use of this technique in those times. During Renaissance, however, treatises on architecture brought to light recommendations on this construction technique. As usual, the humanist and architect Leon Batista Alberti, in his pioneer work *De Re Ædificatoria*, recommended the use of wood piles and for the first time established the empirical parameters for their dimension and application. He stated:

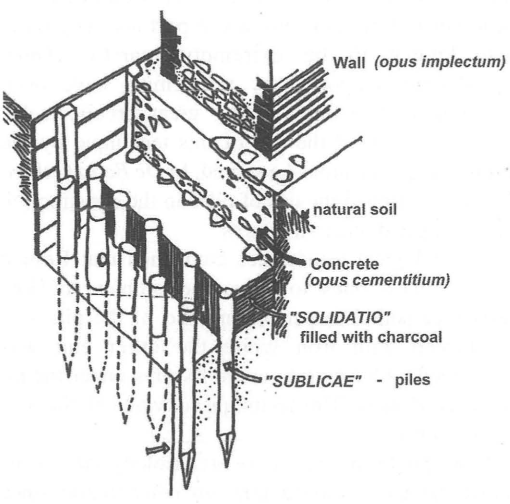

Figure 2
Basic system of foundations on piles (Cairoli 1995, 128)

> Si configgano molti pali e pertiche, dalla cima abrustolita, com la base rivolta in alto, in maniera tale Che l'area di quest'opera venga larga il doppio di quella che dovrà essere il muro; i pali devono essere lunghi almeno 1/8 dell'altezza che si vuol dare al muro, e grossi non meno di 1/12 della propria lungezza[2] (Alberti, trans. Orlandi 1966, 184).

Following Alberti many writers of classic treatises on architecture recommended the same technique be used in low-resistant soils. Noteworthy among these writers is Andrea Palladio *da Vicenza* who said:

> Ma se'l terreno sara molle, e profonderà molto, come nelle paludi; all'hora si faranno le palificate:i pali delle quali saranno lunghi per la ottava parte dell'altezza del muro, e grosssi per la duodecima parte dela loro lunghezza. Si deono ficcare i pali si spessi, Che fra quelli nove ne possano entrare degli altri: & deono esser battuti com colpi piùtosto spessi, Che gravi, accioche meglio venga à consolidarsi il terreno, e fermarsi[3] (Palladio 1570, 10).

As far as the dimensions, Palladio repeated the same empirical recommendation made by Alberti. The same view regarding reinforcing foundations can be found in the work of Vincenzo Scamozzi (Scamozzi 1615, 2: 286) as well as in the work by other writers.

A 17th century drawing by a military engineer and housed at the National Library in Lisbon, Portugal,[4] Figure 3, shows a detail of the use of piles. Since the drawing is represented in a graphic scale, it allows some interpretations. Clearly, the piles were not driven as close together as recommended by older treatises, possibly because of the variation in soil-resistance and the weight the foundation would bear. The piles in this drawing show length and diameter approximately equivalent to the old specification (1/12). The piles are topped by the traditional wood frame. Evidently, not all soils are identical to the soil of the Venice Lagoon that required 16.000 piles to support the two foundations of the Rialto Bridge. But Venice is a special case because practically the entire city has its buildings laying over piles which the specialized literature affirms to be larix (may be *Larix decidua*).

The end of the 16th century and the beginning of the 17th century witnessed the birth of military engineering followed by new concepts on fortifications with bulwarks whose more complex architectural plans often required building in less trustworthy soils. Military engineers followed the classic treatises and continued to use the same recommended technique to stabilize the soil. To avoid a tedious reference to the dozens of treatises of military engineers that flourished in Europe, we limit our comments to the Iberian Peninsula since the practices used there lead to the Brazilian practices that closes this paper.

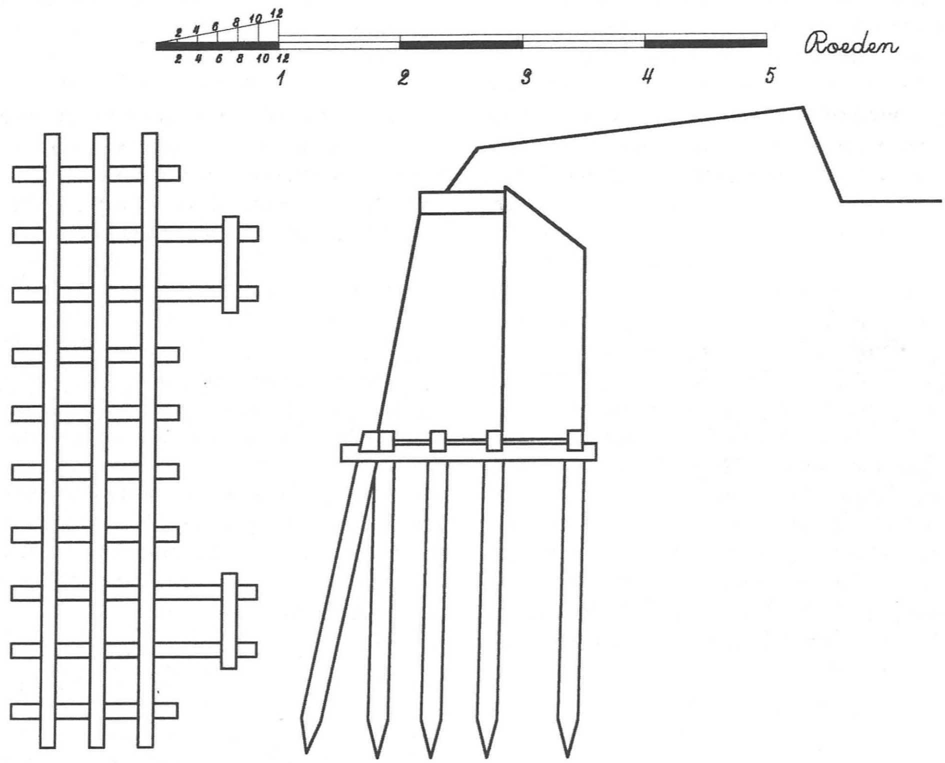

Figure 3
Drawing representing reinforcing piles (scale in Dutch rods) BNL, D-250 P

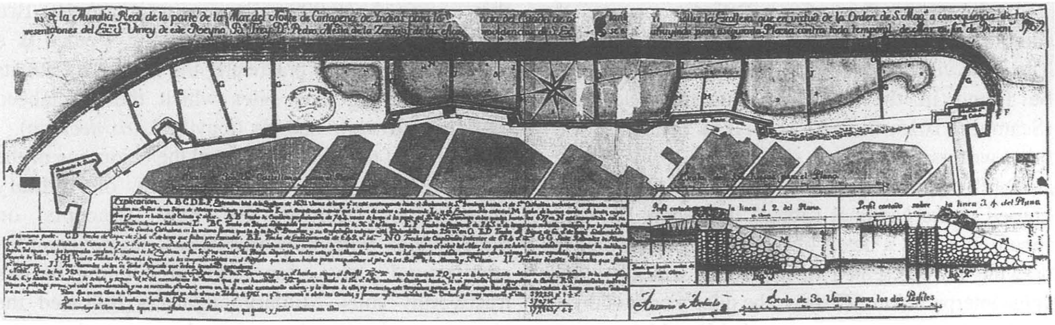

Figure 4
Cartagena de Indias, Colombia-Drawings of fortifications signed by military engineer Antonio Arévalo in 1762. Piles are used to reinforce foundations of fortifications against the sea and enemy landing

The seed of the Spanish and Portuguese fortifications came from Italy, a country associated with Spain through technical and cultural ties in addition to dominion of territories; however, it was the *Academia de Matemáticas y Arquitetura Militar* (Academy of Mathematics and Military Architecture) that in 1582 became the first school to formally train military engineers. Many illustrious professors taught at the academy, among them Juan de Herrera, Firrufino, Cedilho, Juan Ángel, Cristóbal Rojas, Spanocchi. Other schools followed the academy such as the *Escuela de Palas* (Palas School), 1630, the *Academias de Castilla y Andalucía* (Castile and Andalusia Academies), 1635, the *Academia de Matemáticas Española* (Spanish Mathematics Academy), Milan, 1630, the *Academia Real y Militar del Ejército de los Países Bajos* (Royal Military Academy of the Army of the Low Countries), 1675, the *Real y Militar Academia de Matemáticas de Barcelona* (Barcelona Royal and Military Academy of Mathematics), 1710, (Zapetero 1985, 66) and others. As a consequence, the construction techniques described in the classic treatises were very influenced by Italian writers were delivered to new generations of engineers in Spain as well as in Spanish America. In these countries many buildings foundations were reinforced by piles. It is possible that the use of piles was more prevalent in the Spanish America because of the presence of marshy or low resistance soil as it is the case of Mexico City.

The father of the Portuguese military engineering was without doubts Luis Serrão Pimentel, the inspirer of the first school of military engineering founded in Lisbon shortly after the Restoration. The most well-known version of the Portuguese treatise *Método Lusitânico* (Lusitanian Method) (Pimentel 1680) however, makes no reference to the use of piles as a technique to reinforce foundations since the focus of this treatise is the design of fortifications, not the techniques used to build them. Pimentel recommended the use of piles and wood frames in the construction of platforms for the cannons because of the low resistance of the soil of the terreplein. On the other hand in a work entitled *O Engenheiro Português* (The Portuguese Engineer) (Fortes 1729, 2: 278) another distinguished Portuguese engineer —Manoel de Azevedo Fortes— made specific reference to the use of piles. Azevedo Fortes addressed the characteristics of the soil and recommended methods to probe the soil. In his opinion «weaker and soft soils» required the use of frames nailed to the top of the piles with large headless nails (Fortes 1729, 280). Azevedo Fortes considered oak and cork oak as the best types of wood to be used as piles, adding that a certain type of pinewood known as «*pinho da terra*» had also resisted well under water and under the blows of the «*bogio*» (pile drive equipment) (Fortes 1729, 2: 281).

The use of pinewood piles was also recommended by other Portuguese engineers, among them Carvalho de Negreiros. In one of his unpublished treatises on architecture Carvalho de Negreiros prescribed foundations on freshly cut green pinewood piles that should be driven into the soil in a way that the water would not exceed one palm and ¾, or twice the width

of the piles.[5] It is interesting to see that he did not recommend the reinforcement with iron because the oxidation of the metal could damage the wood. Nevertheless, he mentioned that iron-reinforced piles were used in some places of the foundations of the Praça do Comércio (Commerce Square) in Lisbon during the constructions directed by Carlos Mardel.[6] The exclusive use of piles made of pinewood can be confirmed by excavations around most of the buildings in the *Baixa Pombalina* (Pombal's Basin) in Lisbon.

As the wood piles are above all subject to the decomposition and attack by aerobic microorganisms, in general their use has been recommended below the water level. Usually, they have been used as piles working through lateral friction, but they sometimes work through point resistance. In this last case, special care was taken to avoid damages due to driving excesses, the hammer height being reduced above all and using hammer weights not inferior to half the weight of the pile, but never superior to its weight.

When the piles are driven through soft clay or silt soils until reaching more consistent soils, in depths smaller than 20 diameters, an adhesion coefficient of the order of 0,5 should be used. Penetrations inferior to 10 diameters should not be used. The type of pile material has little influences on the adhesion coefficient.

Of course the working load of a group of piles in clay cannot only be estimated based on the behavior of an isolated pile, because the effects of the elapsed time, of the disturbance and of the scale for a single pile is very different than for a group of piles.

To verify a rupture in block, the hypothesis often used that admits the behavior of the group is equivalent to that of a virtual mat foundation resting on 2/3 of the length of the piles and occupying an area that bounds the group of piles.

When wood piles are driven through layers of soft clay to firmer layers, the piles will be submitted to the effect of the negative lateral friction, besides the structural loads.

In cases where a superficial layer of soft clay is present (N_{SPT} between 3 and 5), an approximate estimate of the bearing capacity (Q_u) and of the working load (Q_a) of those piles ($D \cong 0{,}20$ m and $L \cong 2{,}40$ m) can be made, for the project criteria recommended empirically by Alberti (L/H = 1/8 and D/L = 1/12), based on the method of Décourt-Quaresma (1982, 1: 23) and in the verification of the rupture in block.

Thus:

$$Q_u = Q_p + Q_l = 120 N_p \frac{\pi D^2}{4} + 10\left(\frac{N_\ell}{3} + 1\right)\pi D L \cong 15 + 27 \cong 42 \text{ kN}$$

$$Q_a = \frac{Q_p}{4} + \frac{Q_\ell}{1{,}3} \cong 24 \text{ kN}$$

In the case of a reinforcement with a framing of approximately 1 m × 5 m, the working load would be of the order of 400 kN, as follows:

$$Q_{a\,(group)} = 0{,}6\ n\ Q_a = 432 \text{ kN}$$

$$Q_{a\,(block)} = s_a\, A_{block} = 20\, N_{SPT}\, A_{block} \cong 400 \text{ kN}$$

Pile drive machinery

As mentioned above Vitruvius already referred to pile drive machinery,[7] but since the illustrations were not preserved with the text, one can only make conjectures as to the pile drive machinery, as did Perrault. Perrault's conjecture does not render invalid the hypothesis that metal sledgehammers were used to drive piles in the soil. After the first half of the 17th century there is an extensive list of pile drive machines with drawings by their manufacturers, some more realistic than others, and some very elaborate and represented by excellent technical drawings. One of them was presented by Alessandro Capra, an architect and military engineer from Cremona and a machinery expert who served in Italy the army of Spanish King Philip IV. In the reprint edition of Capra's treatise on architecture (Capra 1717, 267) there is a model of a pile drive machine that more or less illustrates how this machinery worked in the past. The same is not true of Giovanni Branca's visionary project for a machine moved by hydraulic power and to be used in swampy areas (Branca 1629).

As far as contributions from the Spanish engineers to this topic many examples of interesting drawings can be found in the *Archivo General de Simancas* (Simancas General Archive), Spain.[8] Dalambert and Diderot's French Encyclopedia also has a rich repertoire of pile drive machines.

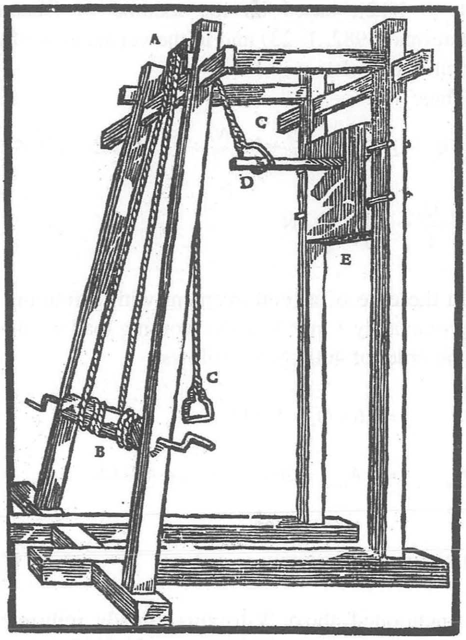

Figure 5
Capra's pile drive machine (Capra 1717, 267)

Colonial Brazil was extreme poor in written technical information. Even Brazilian scientists as Mathias Ayres Ramos d'Eça made his publication in Portugal. The only remaining source is the very interesting manuscript by Brigadier Diogo da Silveira Velloso, who wrote the work in Recife, Pernambuco, Brazil. The manuscript is part of the collection of the Biblioteca da Ajuda[9] (Ajuda Library, Lisbon, Portugal). Velloso includes recommendations on the use of piles to reinforce foundations. As a follower of Vitruvius (whom he considered to be *without doubts the master of civil architecture*),[10] and other authors of Italian treatises, Velloso's recommendations repeated the same empirical parameters defined by Alberti, three hundred years before, i.e., that the area where the piles are driven must equal twice the width of the wall; the length of the piles must be at least 1/8 of the height of the wall and the thickness at least 1/12 of their own length. Following Alberti, Velloso also recommended that the piles were pound down into the soil.[11]

The Systematic investigation of the historical archeology in Brazil, limited regarding quantity, has not yet yielded a proof to this construction technique

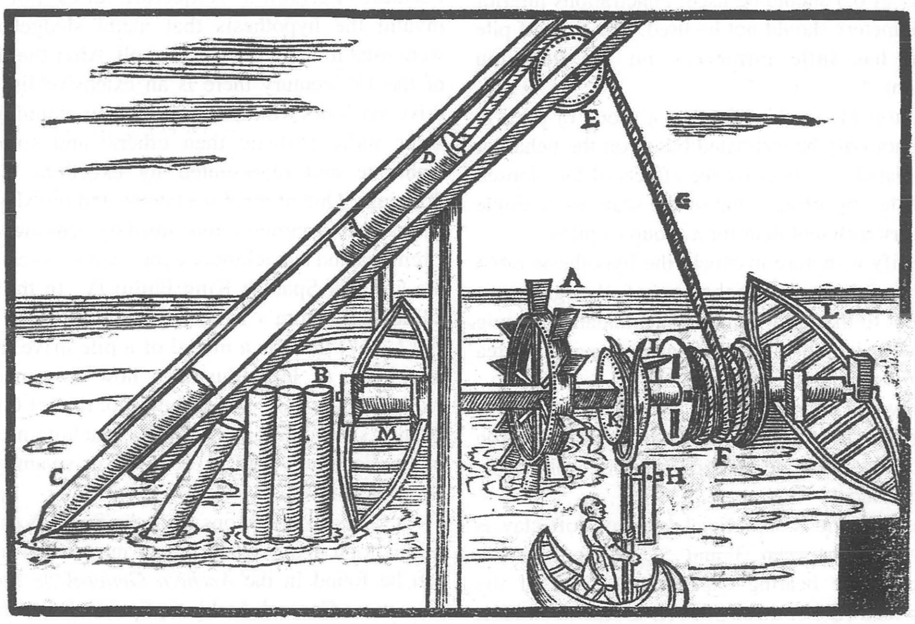

Figure 6
Pile drive machinery from Giovanni Branca's work (Branca 1629)

Figure 7
Actual cracks in piles zone

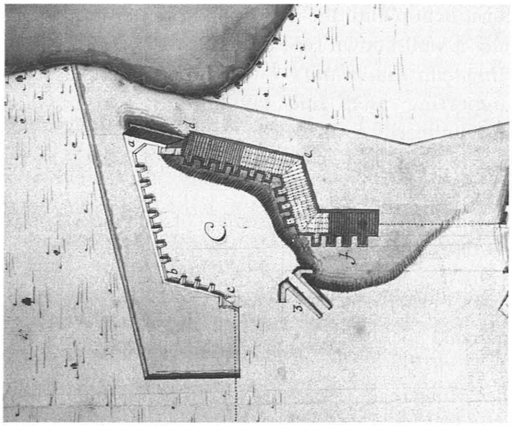

Figure 8
State of the construction in 1766 (AMRJ)

that, as previously seen, has been used for thousand of years in other countries. On the other hand, there is documented proof found through the observation of a concrete case.

The fort of *S. José de Macapá* (St. Joseph of Macapá Fort) in the state of Amapá in northern Brazil, is one of the most important military monuments. Not only the plan but also the scale make this fort remarkable. Soil analysis conducted in preparation for the current restoration of the fort identified low-resistance argiliferous soil on the north side of the fort (sediments from the Amazon River). The iconographic documents of the area shows an old *igarapé*[12] formed by the waters of the great Amazon River.

Exactly toward the direction of the previous marshy area one can observe wall lesions in the vicinity of the St. Joseph bastion, Figure 8. A long time ago the structure had been reinforced with discharge arcs made of bricks.[13]

These lesions and the reports of soundings led all to suspect that at least part of the foundations of the fort were pile-reinforced. In an attempt to clarify the issue through historical investigation pertinent drawings were found on a 18^{th} century report of the progress of the construction. As suspected, these drawings clearly demonstrated the use of piles in the foundation. The oldest of the drawings shows only the bastion and the place where the piles were to be driven.

A subsequent research in the Brazilian Army Military Archive disclosed a specific image of piles being used to reinforce a foundation, Figure 8, with details shown on Figure 9. The piles are square shaped because are cut from large trunks. The spacing of the piles shows peculiar details. The face to face longitudinal distance of the piles was always the same, the equivalent to 4 3/4 palms (1.045 m). The transversal distance from axle to axle varied from 4 palms (0,88 m) in high-stress areas that supported the wall, to 4 $^{1}/_{2}$, palms (0,99 m) in the counterfort area, and to 4 1/24 (0,92 m) in the inclined area of the wall (scarpment).

In Brazil there is a great variety of wood[14] that resist to decay even when buried. The easy access to this type of material lead to its wide use in

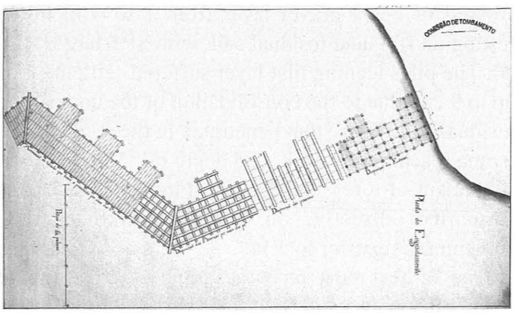

Figure 9
«Pile Project», Fort S. José de Macapá (18^{th} century). Brazilian Army Military Archive-11.03.2327

construction until the 1950's and even later on. Even later a well-known type of wood —*Beriba* or *Biribá* (*Duguetia lanceolata*)— was heavily used as piles supporting piers and landing docks. *Biribá* is extraordinarily resistant and for this reason popular. It is now an endangered vegetal specie protected by the Brazilian Government.

Among countless examples of important constructions of more recent periods with wood piles it is worth mentioning the customs building of the of Rio de Janeiro (1866), built on wood piles driven by a steam operated pile drive (Vargas 1996, 35); stretches of the docks of Rio de Janeiro (1866) and of Santos (1891); the Municipal Theater of Rio de Janeiro (1905); countless buildings from 6 to 8 stories in the flat land bordering the rivers Tamanduateí, Tietê and Pinheiros, in São Paulo (Teixeira 2000, 1: 9), many buildings of the Lower City of Salvador and so on. At the beginning hardwood was used but with the shortage of the rarest species eucalyptus started to be used.

A foundation that deserves special mention was built, in 1959, for the COSIPA sheet-metal ovens, with the driving of about 7.000 wood piles from 11 to 13 m topped with a 1 m thick rigid mat foundation measuring 33,50 m × 163,50 m. The largest problems faced in these piles foundations, crossing layers of soft soils, resulted in the lateral stress of negative friction coming, as much from the vertical settlement of the clay under the weight of the embankment (that arrives to have 7 m of thickness) as from the disturbance due to the great concentration of piles. This concentration also caused lateral displacements of the piles, it is tended measured where values of up to 10 cm of displacement were measured (Teixeira 2000, 1: 13). Depending on the type, the driven piles crossed or not a gravel layer from 1 to 4 m thick, resting on silt-sand residual soil, with SPT larger than 30. The piles leaning that layer suffered settlement of up to 9 cm, due to the consolidation of the underlying residual soil. Those that penetrated in the residual soil (some reaching the rock, to a depth of 35 m) suffered settlement of a few millimeters. Floors without piles supported directly on the embankment had settlements superior to 1 m.

One of the most recent examples of the use of wood piles is in Itajaí, State of Santa Catarina, in the 90's with the building of 4 «dolphins» destined to the docking of ships. For two of those dolphins 33 «peroba» *(Aspidosperma polyneuron)* piles were driven and for the other two 51 eucalyptus piles were used. On average, the piles had a 23 cm diameter and they were driven to a depth of 18 m.

Final considerations

The foundation system with reinforcement of wood piles, when located below the groundwater level, is a solution that has been efficient in practice along the years.

For grounds that can't support direct foundation, the empiric parameters established by Alberti, to use wood piles at the time seem to be reasonable when compared with the results obtained by modern methods of semi-empiric estimate of bearing capacity.

Notes

1. In other copies of the Vitruvian text the wood mentioned is the willow (*saligneis* from *salignus, a, um).*
2. (Many piles are driven in the soil, the sharp end down, the base up, in a way that the area is twice the width of the wall; the length of the piles must be at least 1/8 of the height of the wall and the thickness at least 1/12 of their own length).
3. (But if the non-resistant soil is deep, as in the swamps, one must use piles whose length equals 1/8 of the height of the wall and whose thickness equals 1/12 of their own length. The piles must be driven so close together that there is no room for inserting a new pile and they need to be pound down into the soil in order to become stable).
4. Digital reproduction of a Dutch drawing housed at Biblioteca Nacional de Lisboa (National Library, Lisbon): BNL, D-250 P.
5. Arquivo Militar (Portuguese Army Military Archive), Mss. nº 3770, 37. Negreiros, Jozê Manuel Carvalho de. *Jornada pelo Tejo*. One can conclude that the proposed diameter was ≈ ∅ 0,19cm.
6. Architect and military engineer of Hungarian descent who worked for the Portuguese government during the 18th century and arrived in Brazil in 1733.
7. [...] *sublicaque machinis adigatur quam creberrime* [...]
8. Archivo General de Simancas (Simancas General Archive). Drawings by Francisco Ricaud de Tigrales 1756: Floating platform for the pile drive machine, ref. M.P. y D.XLIV-9 and automatic release mechanism for the pile drive machine, ref. M.P. y D.XLIV-10.

9. Biblioteca da Ajuda (Ajuda's Library), Mss. (49-III-3), 1743. VELLOSO, Diogo da Sylveira. *Architectura Militar ou fortificação moderna.*, Lisboa.
10. Idem, Cap. 24, fl.210v.
11. «Se o fundo do alicerce for pouco firme, e paulozo (sic.) se cravará de estacas em dobrada largura do que há de ser a parede, e as ditas estacas terão de comprido ao menos a *outava parte* do que há de ser a altura da muralha, e terão de grossura o que corresponde á *duodecima parte* de seu comprimento antes mais que menos; e cravarsehão miúdas metendo entre ellas outras estacas menores, athe que não fique lugar de meter mais; cavilharsehão com outros paos atraveçados, e principalmente por fora, enchendo os vãos com cal e cascalho de pedra miúda, e por sima boas lages compridas e largas» (Idem, Cap. 24, fl.218v). (If the bottom of the foundation is not firm enough and swampy we must drive piles in an area twice as large as the designed wall, and the so called piles should have the length of at least 1/8 of the height of the wall and its width should have 1/12 of its length, better more than less; and they will be driven close together and other thinner piles will be driven between them until there's no more place to any other piles. Then they will be jointed with other transverse pieces of wood, especially in the outside, filling in the spaces inside with lime and gravel, and on the top good, large and long stone slabs will be placed).
12. *Igarapé* is a word that originates from the tupy language (*i'ara pé*) and it means waterway: short arm of river or narrow canal.
13. By the way this kind of reinforcement is taught by Alberti on book X. Alberti. *Op. cit.,* 2: 994.
14. Maçaranduba (*Manilkara spp.)*, Pau d'Arco *(Tabebuia spp.)*, Sucupira *(Bowdichia nitida)*, Acapu *(Vouacapoua Americana)* and many others, but mainly the Biriba also known as Pindaíba (*Duguetia lanceolata*) which was the most prestigious one in Bahia (Brazil) with this purpose.

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Spanish ribbed vaults in the 15th and 16th centuries

José Carlos Palacios Gonzalo

Classical historiography separates, aiming at our understanding, historical events in periods discreetly defined. Middle Ages come to an end in 1453 with the collapse of Constantinople and a new period in the history of Mankind, which has been called Renaissance, sees the light: the whole cultural environment which had enlightened the long existence of medieval Europe for centuries seems meaningless and, in a short period of time, transforms itself and imbibes in classical history.

Reality, nevertheless, is utterly different when we analyse carefully the line separating the Middle Ages and the Renaissance. Far from being a clear-cut border, cultural phenomena of both periods intermingle and fuse, sometimes anticipating events, other times keeping alive for centuries. Cultural events ahead of their time, the vanguards, are welcome warm-heartedly, while those that surpass their cultural boundaries are considered late offspring, therefore looked down upon.

One of those remarkable anachronisms is represented by the use, along the 15th and 16th centuries, of ribbed vaults, the unrightfully named late-gothic vaults. In Spain and in the rest of Europe, quite many architects, experts in all the aesthetic and building resorts of classical architecture, insist in the use and development of a ribbed vault of medieval origin. It is stunning to note that, despite the large amount of works built in that style, this long chapter in the history of Architecture has been considered eclectic or mannerist, and, therefore, despised upon. This lack of interest can be put down on to the apparent anachronism of its existence and to the fact of its surpassing the boundaries of the Middle Ages.

The study of medieval architecture reached its summit with Viollet-le-Duc who, fascinated by French gothic architecture, analyses in a magnificent way the geometrical and building aspects of the classical gothic vault prevailing in the region of Paris along the 12th and 13th centuries. Choissy takes largely up Viollet's explanations and interprets, on expounding the multiplication of ribs in vaults, that the great gothic vault starts its decline when the virtuosity and mannerism of builders put an end to the rationality and simplicity of the first ribbed vaults. Both authors neglect the fact that France, after the 100 Years' War and the Black Death in the middle of the14th century, goes through such a strong crisis that its population retracts to the density of the 11th century; forests spread out again and occupy the French territory. Its *flamboyant* architecture resents from those dramatic circumstances and enters a period of lesser importance in the European context which will last all along the 15th century.

Spain, instead, expands a lot on the economic side and will reach the top of the European monarchies, its architecture reflecting its economic growth. The influence of Renaissance pervade building techniques in Spain developing a remarkable architecture «*a lo romano*» (made in Roman style) while maintaining spectacular architectural works of medieval inspiration which, surprisingly, was called «*moderna*»

by the architects of the time. Eloquent examples of gothic architecture designed in Renaissance are the cathedrals of Salamanca, Segovia or Sevilla.

This presentation aims at studying in depth the term *moderno* applied by contemporary architects to their designs: modern as opposed to what?. Careful analysis of those architectural samples leads us to appreciate its modernity compared to the gothic style of the Paris region which had inspired in Spain the cathedrals of Burgos, León and Toledo. Our 15th and 16th centuries architects when building their vaults crammed with all kinds of ribs considered themselves utterly different from the constructors of the 11th and 12th centuries' cathedrals.

The present study focuses on those differences seeking to establish a link between the complex morphology of that type of vaults and its construction. In the first place, we will show the composition of the ribs' patterns to further relate it to the shape and volume of the vault surface. This study reveals interesting links between both aspects letting us discover the wise and varied use of the vaulted shapes in complex surfaces which differ a lot from the classical shells of French gothic style.

The study should be divided in three different chapters:

- Morphological analysis
- Modulation
- Volumetry

Morphological analysis

The first thing that comes to mind when we see the arch-like structures of this period are the complex designs that create the array of their fan-traceries. Their designs, however, seem to follow highly defined patterns that we will show afterwards.

Although we do not intend to go deep in the historical analysis of the 15th and 16th centuries' vaults, let us recall that the Spanish ribbed vaults of this period can be grouped in two series, formally very different; in the first place, the vaults of rectilinear geometric designs and, secondly, those that present curvature in their ribs. These two large groups of vaults are connected, respectively, to two main schools of stonecutting: the Toledo school related to Juan Guas and Enrique Egas and characterized by the use of straight-lined designs and the Burgos school, with more complex and sophisticated vaults after Simón de Colonia renewed its designs.

From a different point of view, we can also point out that the vaults' designs can be classified in two groups: those whose design is centralized around the middle key and those where the secondary ribs' network interconnects various vaults forming a *continuum* (grid). The polar patterns, the German *sterngevölbe*, had an enormous success in Spain where the overall presence of the crossing arches cuts down clearly the aisles' length. Secondly, the reticular designs, the *netzguewölbe,* so frequent in Central Europe, were scarcely relevant in our country. The exception to this rule is, perhaps, Juan de Álava that designed remarkable examples of vaults where the curved ribs interconnect the different sections creating astonishing and highly sophisticated networks.

After these general considerations, we can conclude that the designs of Spanish vaults follow a set of compositional rules divided in three groups:

- the tierceron on the bisecting line:

  The most widely used pattern: once the diagonal arches drawn on the ground plan, the tierceron is placed on the bisector of the angle created between the diagonal arch and the crossing arch. To place the bisector, a surprising geometric construction is used: a circumference is designed around the plan of the vault, the axes of symmetry are prolonged and, where these axes cut the circumference, a straight line linking this point to the vault vertex is drawn; the straight line coincides with the bisector and its layout determines the position of the tierceron.

  This way of placing the tierceron can be seen as much in vaults of square plan as in those of rectangular plan. (Fig. 1)

- the regular pattern:

  Probably of Germanic origin, it often appears in German vaults as a basis to arrange the complex designs of reticular vaults (*netzguewölbe)*. In Spain it is also a regulating element in the polar vaults and in those of rectangular plan where very often the idea of placing the tiercerons on the bisectors is abandoned. Its use gives the possibility of

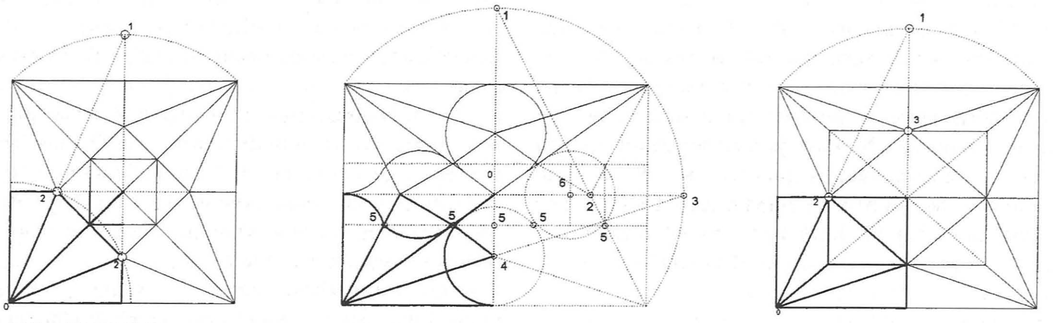


Figure 1
Three examples of vaults where the tierceron arches are placed in the position of the angle between the diagonal and the crossing or former arch

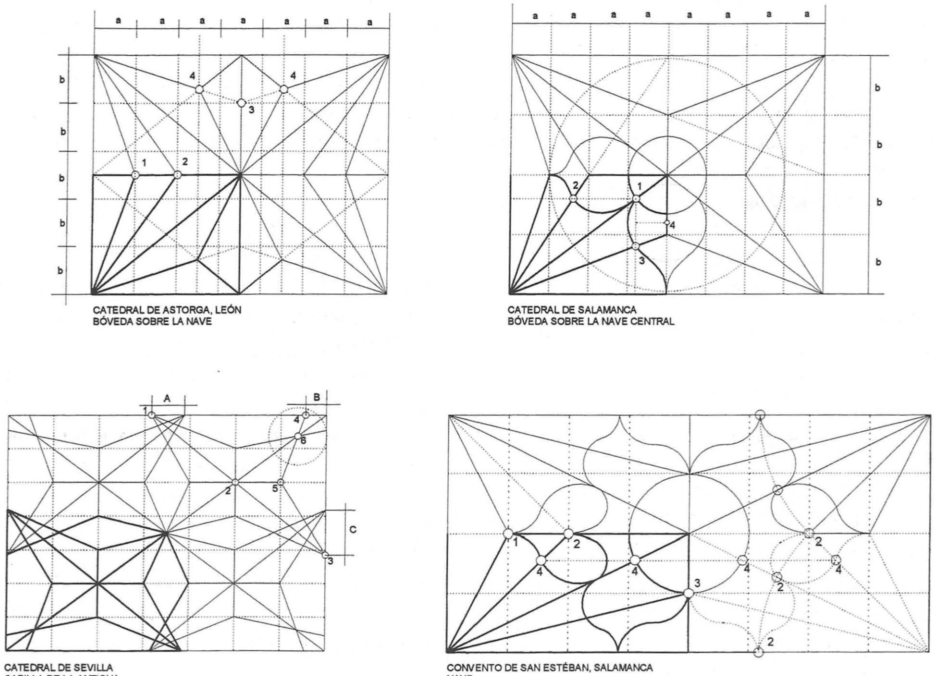


Figure 2
Four vaults of design established according to a regular pattern

fragmenting the plan of the vault orderly and identifying strategic points to place the vault keys. The frames can be square or rectangular, being the more frequent ones: 434, 634, 834, 8x8 or also 735 or 737, although there are other more complex combinations in which half values are used.
One should know that occasionally the two design rules mentioned can occur in the same vault. (Fig. 2)

• the alignments:
This is a secondary resort, used once the large arches have been placed according to the previously mentioned methods. As a general rule, it is used to determine the position of the crossings of secondary ribs such as the curved arches and links, either amongst themselves or with the main arches. The principle of this rule is based on the criterion that all keys must be interlinked and therefore must never be placed at random. (Fig. 3)

MODULATION

The two fundamental regulating systems on which the medieval composition is based are well known: *«ad cuadratum»* and *«more germanicum»* depending on whether we adopt a geometry based on the rectangle or one based on the triangle. The general composition of the most remarkable buildings of this period, on plan as well as in section and in elevation, was carried out according to these two systems. The regulating system based on the triangle appears freq in Central Europe, especially in Germany, while our country seems to remain faithful to the regulating sketches based on the square.

Apart form these general systems, another interesting aspect stands out: the modulation. Although we do not intend to go into detail thereupon, let us recall the medieval sensitivity to establish series of harmonic numbers that ensured the perfection of architectural works. We are familiar

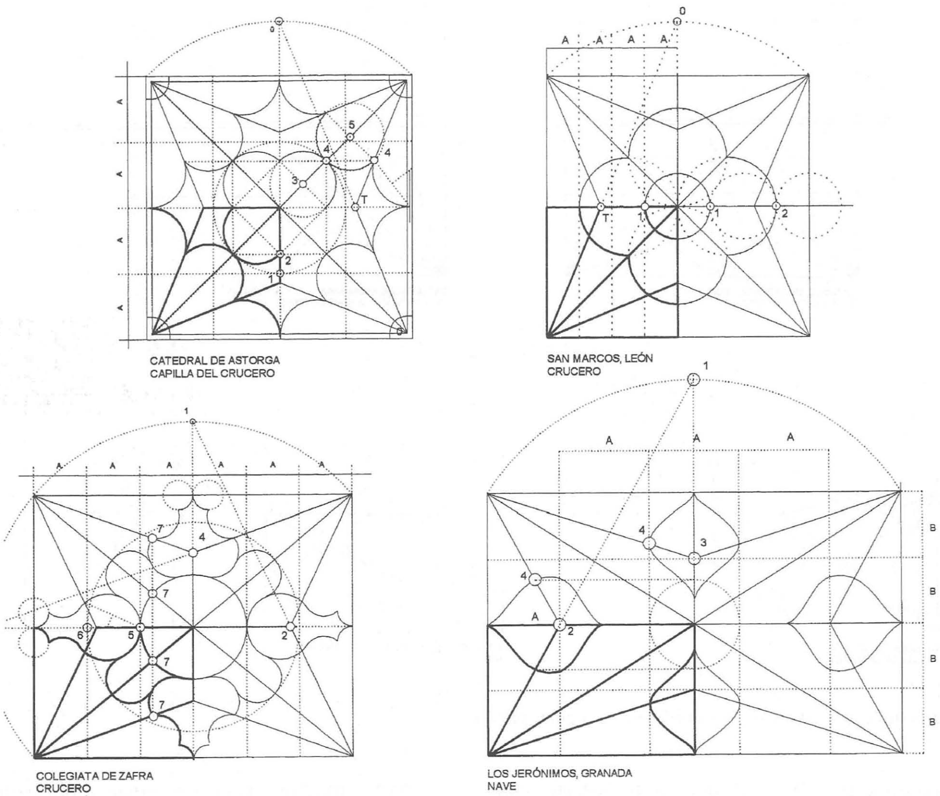


Figure 3
Four examples of vaults where the design is based both on the bisecting line and on the use of a regular pattern. On vaults 2 and 4 the alignments of their subsidiary keys can be seen

with some of these series based on the aureus rectangle, on the square root of 2, etc. However, the series that seems to have been largely used in our country is one that starting from a rectangle of which the longer side is twice as big as the shorter, that is to say with a relation between its sides of 1:2, generates a series of rectangles when having each side increase a unit 2:3, 3:4, 4:5, 5:6 . . . and so on.

The series starts, therefore, from two squares joined in a rectangle in which, logically, the longer side is twice as long as the smaller side. So, each rectangle of the series tempers the differences of its sides until, *ad infinitum*, we would find a single square.

In this huge amount of rectangles there is one reaching the top of perfection: the one with the proportion 3:4, named the *sexquitercia* proportion. This rectangle is formed when joining by the diagonal line two triangles with sides 3, 4 and 5; we are talking about the famous triangle of Pitagoras that since old times was considered the perfect triangle and even holy by Egyptians.

Besides the above mentioned rectangle, the series contains others of interesting proportions that deserved a specific name:

Dupla	1:2
Sexquiáltera	2:3
Sexquitercia	3:4
Sexquicuarta.	4:5

Out of the infinite rectangles potentially contained in this series, we can affirm, once the measures had been taken, that the format of the Spanish vaults complies mostly with one of those previously pointed out. (Fig. 4)

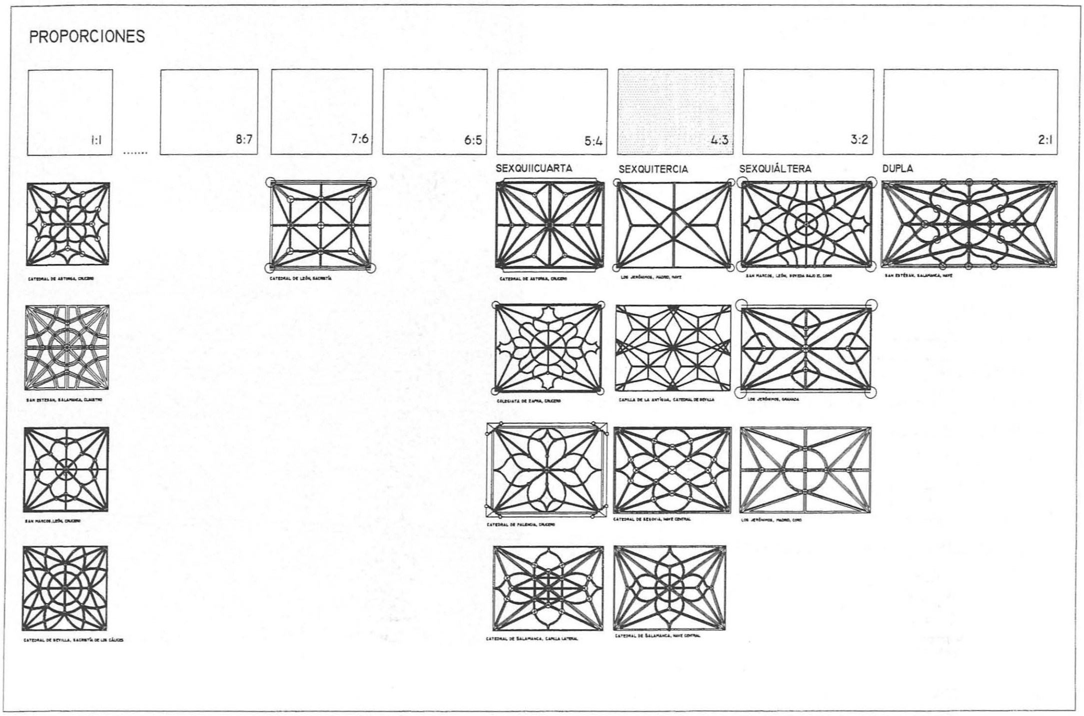


Figure 4

VOLUMETRY OF THE VAULT

The third part of this presentation focuses on what has been considered one of the most remarkable characteristics in the construction of late-gothic vaults, that is to say the volumetry of the vault.

In either the rectangular or square plan French gothic vault, the diagonal arch was always semicircular. This arch determined the height of the central key and, as a general rule, the height of the keys of the former and crossing arches that were to coincide with the central key; therefore, the profile of this type of vault, in the region of Paris, was basically flat. Although in the south of France, specially in the Aquitaine region, there were vaults with a rather round pattern, the vault previously described is the main classic vault of French gothic architecture.

In the 15th century, having elapsed three centuries after the appearance of gothic style in France, the ribbed vault had developed considerably, not only due to its complex design of ribs on the horizontal level, but also to the appearance of a remarkable repertoire of vaulted surfaces to which the architect can resort to carry out the vault.

As we mentioned on other occasions, the increase in the number of arches is justified, from the point of view of construction, as an ingenious attempt to eliminate the centering necessary to build the panel work. Although some hypotheses have been anticipated, we do not know yet precisely how the filling of the panels in the large French vaults was made. Multiplying the ribs solves this problem because it allows the workstone of the panels to rest comfortably amongst them without needing expensive ancillary means of scaffolding and without resorting neither to bulging or vaulting the panels. Because of all this, we can consider the network of ribs like a lost centering made in stone. As it happens frequently in architecture, a necessity imposed by construction can attain higher categories and become a tool of design with a language of its own.

Nevertheless, the increasingly sophisticated designs of ribbed vaults require specific constructive solutions of vault shapes to be carried out; think, for example, of the pointed barrel vaults for the designs in network or of the rounded surfaces for the subsidiary ribs. As a consequence, we find a large repertoire of vaults out of which rigorous measuring has allowed us to identify the following types:

- Horizontal ridge vault:

This type of vault takes up the method of the French vault in which the ridge in the two orthogonal sections is practically horizontal; the profile of the vault may be a straight or a broken line. Some architects seem to favour specially this type of vault, such is the case of the architects Hontañón. According to the way it is built, we could distinguish three types of vaults:

1) Traceries in half-circular arches. These arches generally have their centres in the impost lines although sometimes all or some of the centres are placed on a higher level resulting in a raised vault. (Fig. 5)

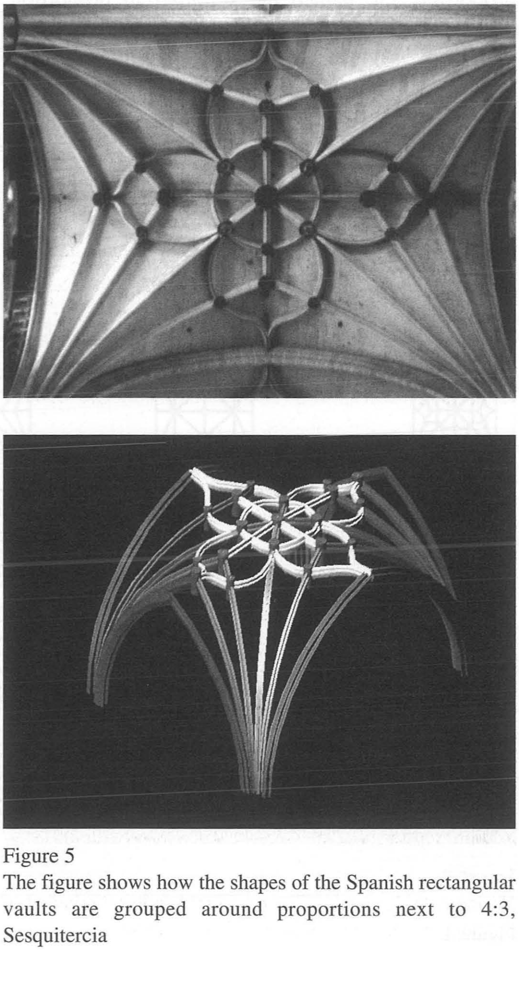


Figure 5
The figure shows how the shapes of the Spanish rectangular vaults are grouped around proportions next to 4:3, Sesquitercia

2) Traceries made with two-centered arches: in this case the ridges are rigorously horizontal and the arches of the tiercerons have two centres. The springing of all of them is the same portion of an oval, which produces an elegant spandrel stone in fan shape.(Fig. 6)
3) Traceries of flat key panel: Some vaults whose diagonal rib has been removed make possible the building of a horizontal panel in the central boss; this plan can be square or rhomboid and is situated in the same axes of the vault.

• Pointed barrel vault:

Extremely frequent in Central Europe, it was much less used in Spain. It is very adequate in designs of continuous tracery or in network. In these vaults the transversal ridge, in the direction of the aisle axis, must be horizontal and the powerful crossing ribs, so typically Spanish, must reduce their section so as not to interrupt visually the length of the barrel. There are two types:

1) Transverse vaults from the top: the panels reaching the former arches start from the central key (Fig. 7)
2) Transverse vaults at half level: the barrel vault stands out neatly and the transverse vaults are placed at half level, under the horizontal ridge rib, coinciding with a crossing of tiercerons (Fig. 8)

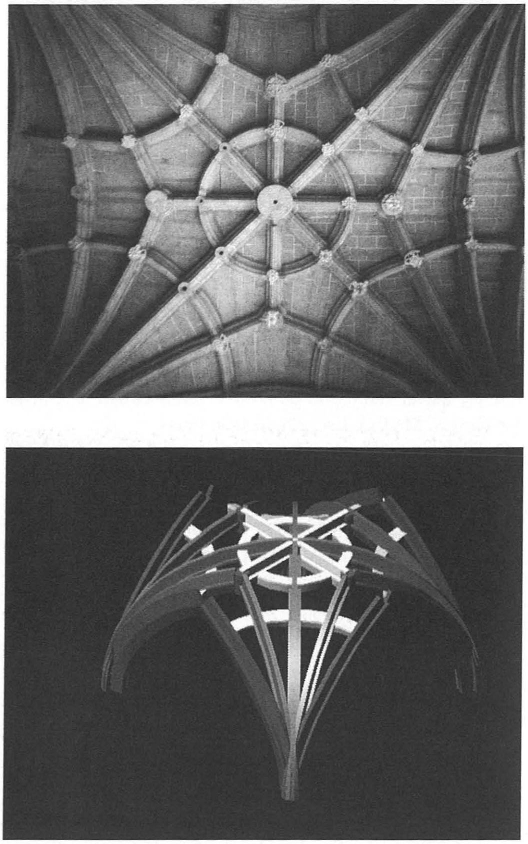


Figure 6
Horizontal ridge vault with one-centred arches. Cathedral of Salamanca, central aisle. Juan Gil de Hontañón

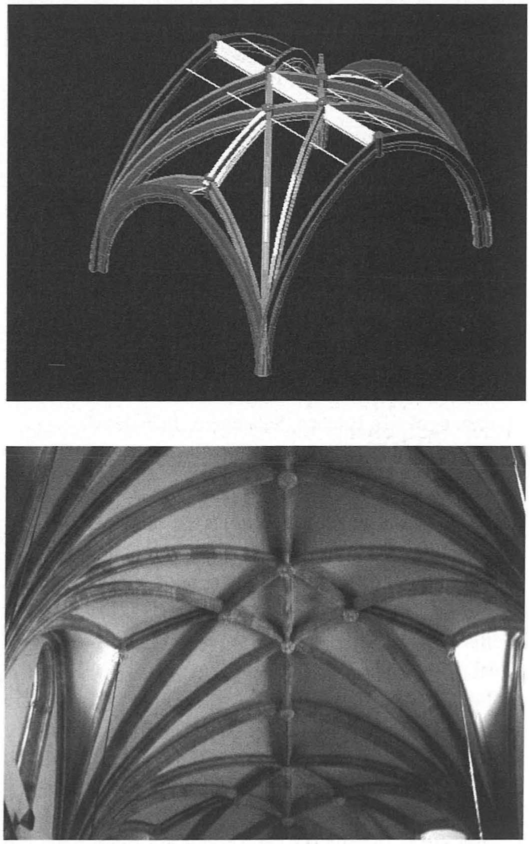
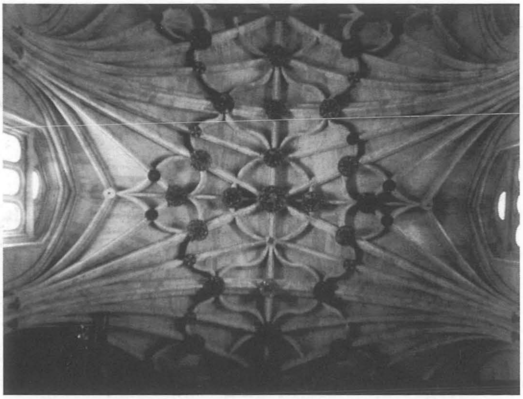


Figure 7
Horizontal ridge vault with two-centred arches. Monastery of San Esteban, Salamanca. Juan de Álava



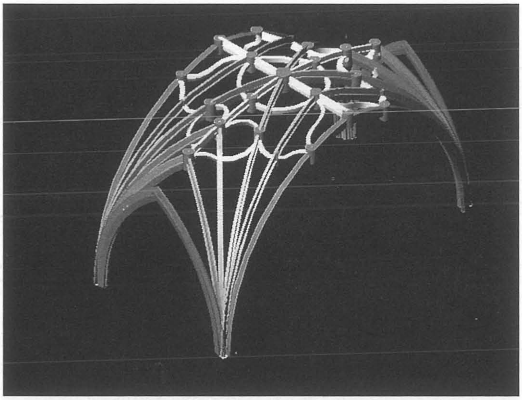
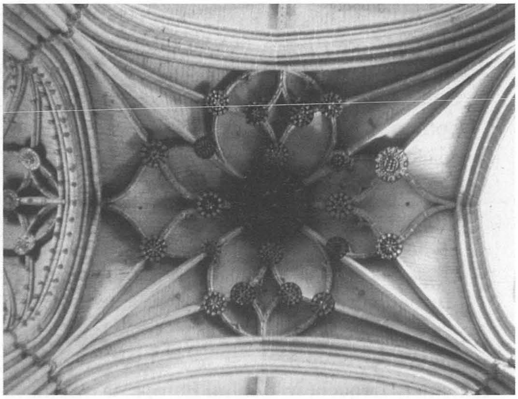


Figure 8
Pointed barrel vault with transverse vaults from the top. Monastery of San Esteban, Salamanca. Juan de Álava



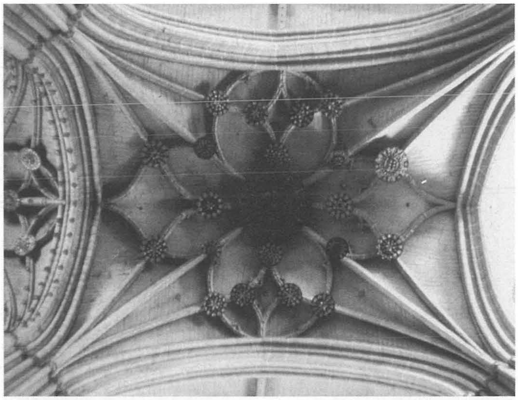


Figure 9
Pointed barrel vault with transverse vaults at half level. Los Jerónimos, Madrid. Escuela de Juan Guas

- Curved ridge vault

Very frequent in the south of France, it was enormously popular in our country. It creates a relatively continuous vaulted surface allowing the traceries to develop without the strong broken lines that make up the horizontal ridge vault. The sections of the vault may be unequal letting the former and crossing arches fully free to reach the heights considered appropriate. In Spain, where there is much light and no need of having large glass windows as in northern Europe, former arches may be lower creating side walls more proportionate to a design of windows substantially more reduced than in Central Europe. (Fig. 9)

- Spherical vaults

The appearance of the circular subsidiary ribs, largely used in the Spanish vaults, resulted in the gothic vault becoming completely spherical: let us draw your attention to the unaesthetic result of a large circular subsidiary rib over the uneven surface of a traditional gothic vault. (Fig. 10)

- Bulging vaults

The rule by which the diagonal arch remains circular and fixes the position of the central key of the vault can be neglected and, on the other hand, the polar key and the rest of the keys can largely surpass the expected heights in a traditional vault. Both listed examples belong to the same architect: Simón de Colonia. (Fig. 11)

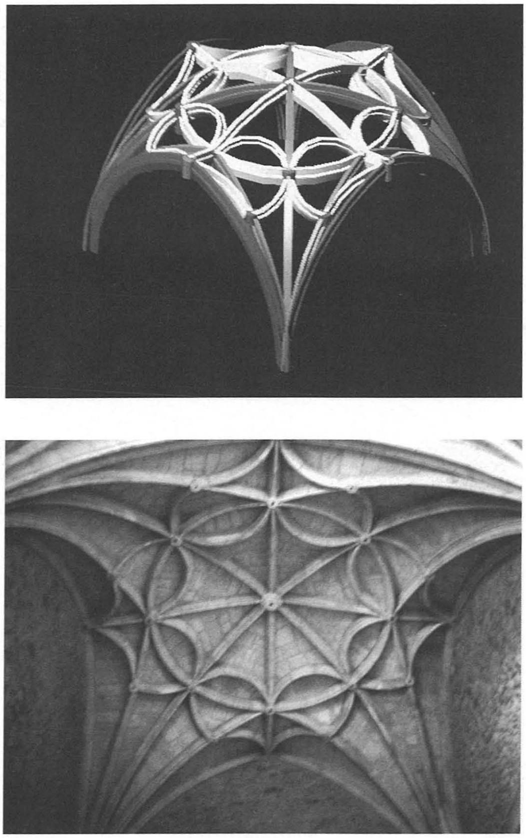


Figure 10
Vaults of round ridge. Cathedral of Palencia, crossing vault. Simón de Colonia

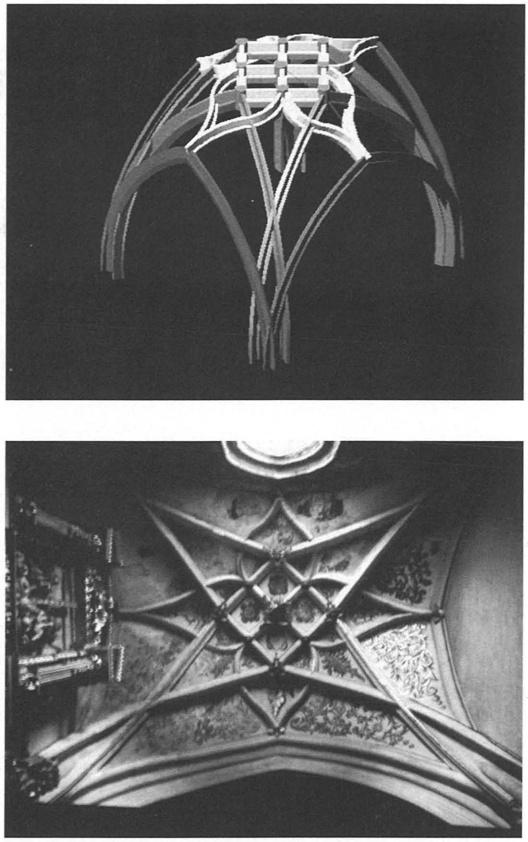


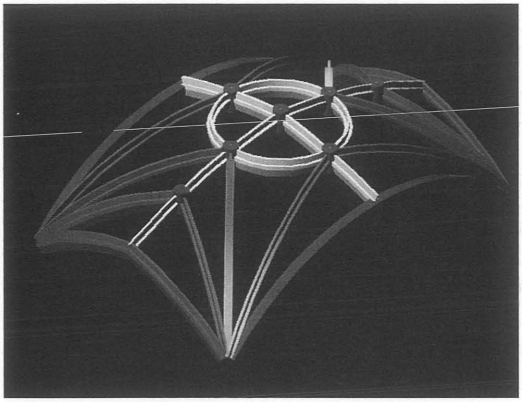
Figure 11
Spheric vaults. Vestry of the monastery del Parral. Segovia

• Flat vaults

The depressed vaults expanded very much in Spain with the introduction of a typology of a typically Spanish conventual church. The choir, that in Spanish cathedrals occupied the central part of the middle aisle and in most European churches was placed in the presbytery, will now find room in a new place at the far end of the middle aisle, on a high gallery under which access to the church is given. This horizontal level, generally of large dimensions, was supported by a series of vaults that had to be depressed in order not to raise this level excessively and to permit visual communication between this platform situated over the entrance door and the high altar.

Concerning the half-centred diagonal arc, we deal with a flat vault when the central key is kept at an equal or lower height than the radius of this circumference. Depending on with which type of arches the vault is built, we can distinguish two kinds of arch:

1) Flat vault of basket arches, made with two-centred arches. (Fig. 12)
2) Flat vault of segmental arches, made with parts of half-centred arch: the segmental arches permit a certain degree of freedom since they can spring with variable angles from the impost level; let us remind you that, on the other hand, all the other arches must remain strictly tangent to the vertical line in the impost level. (Fig. 13)



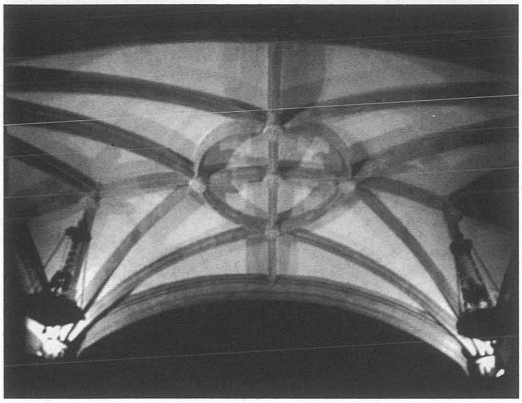
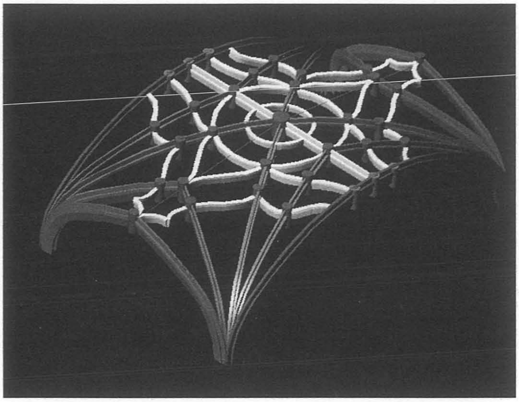


Figure 12
Vaults of bulging ridge. Cathedral of Palencia, Chapel of la Inmaculada. Simón de Colonia



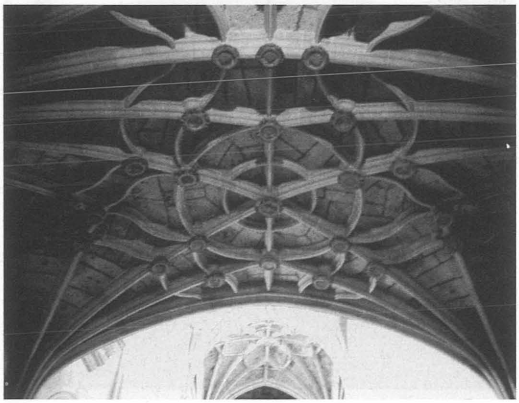


Figure 13
Flat vaults with basket arches. Monastery of San Marcos, León. Juan de Álava

• Vaults in basket arch

Instead of using one-centred arches, the vault can also be built by using two-centred arches, that is to say segments of oval lines. The vault so constructed presents a flattened aspect because its polar key, in general, does not reach the height of the traditional vault; its rounded surface is very appropriate to draw in circular designs. In Spain they are very common all throughout Andalusia. (Fig. 14)

• Convex vaults

In this type of vaults the central key is lower than the key of the crossing and former arches, that is why they have descending instead of ascending ridges. The resulting vault is convex and has four trumpet-shaped quarters in the centre. Rodrigo Gil, who had been lavish with the use of flat ridge vaults designed the example we present. In this case, he reverts the concavity of the vault.(Fig. 15)

In Spain, gothic architects of *flamboyant* gothic cathedrals were not only able to develop sophisticated decorative schemes but also presented a large range of structural patterns for the construction of vault surfaces. 15th and 16th centuries ribbed vaults reveal the high skilled use of geometry by builders: without that know-how, it would have been impossible to

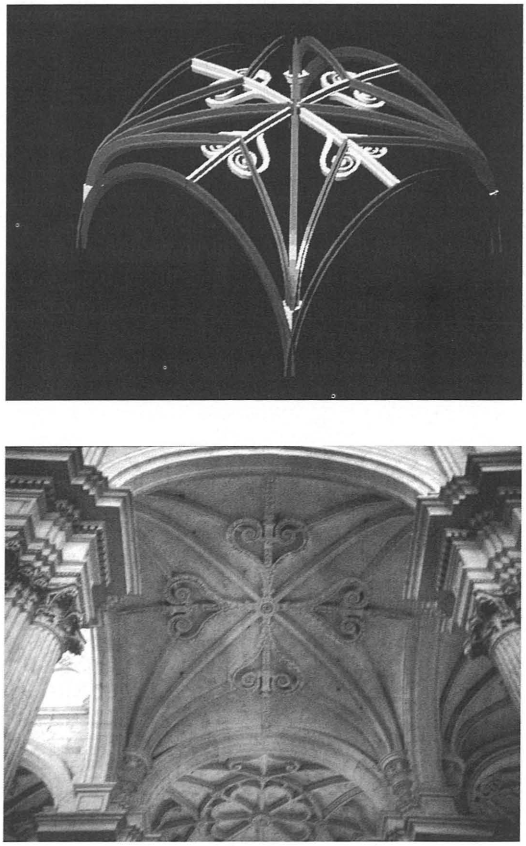


Figure 14
Flat vaults with segmental arches. Los Jerónimos, Madrid. Escuela de Juan Guas

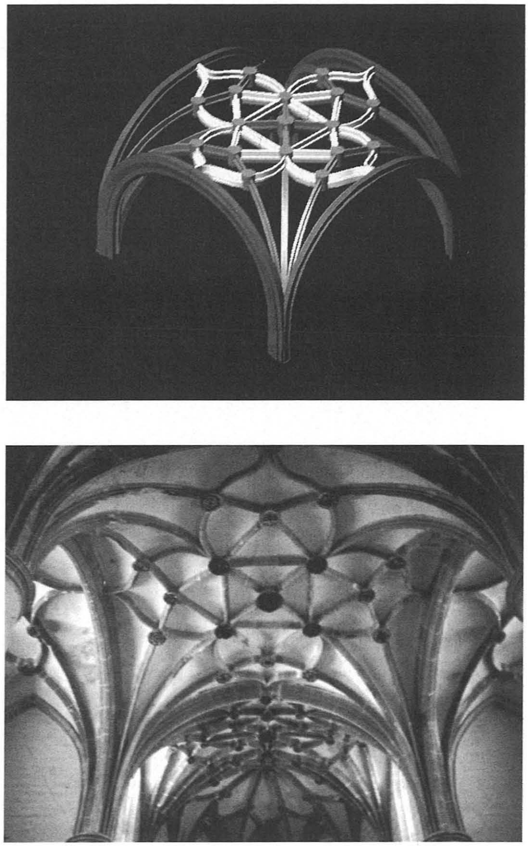


Figure 14
Flat vaults with segmental arches. Los Jerónimos, Madrid. Escuela de Juan Guas

achieve the control of the shape required for the building of a complex vault. Ribbed vaults, Spanish architectural contribution in its most plethoric period in history, cannot obviously be considered a residuary token of the past but one of the most brilliant pages of our architectural history.

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Design and construction of timber roof structures, built over different structural systems. Cases studies at the Valencia Community

Liliana Palaia Pérez

Timber construction was not considered, up to now, a remarkable aspect of the Valencia historical construction. Nevertheless, magnificent examples of coffered ceilings and timber roof structures make reconsider its importance.

Unlike what happens in other regions of the Spanish geography, judging by the existing bibliography on this subject, in Valencia there are a few buildings that count with timber roof structures able to be seen from the interior of the rooms that those protect. The only examples are those timber roof structures constructed on diaphragmatic arches, counting with polychrome coffered ceilings, in the majority of cases.

Other timber structures that are seen from below, are mostly rafter trusses. Therefore, most of the studied cases belong to hidden timber trusses, by means of brick vaults or also by false plaster vaults.

The main differences between timber roof structures able to be seen from below, and those hidden from the sight, are based on its finishing, and on the greater freedom that the carpenters had to create the different roof trusses in each building. Solutions that in any case demanded to the carpenters to know with detail the building that was being constructed, as far as its constructive characteristics and their structural system.

These aspects we will be developed in this paper, applying these criteria to the studied cases.

Determination of the roof structure type

In order to choose the type of roof structure, we have to previously define the range of possibilities that the carpenter had, to adopt one or another design.

We have adopted the classification of the roof structures according to the disposition of elements denominated of 1st order, that is to say, those that are arranged in the first place on the wall structure. Thus we have that these elements can be purlins, rafters or scissors brace trusses. We identified one more group, the mixed trusses, formed by wooden and brick elements.

Purlin trusses consist of a pair of timber beams supported over the walls of different height, thus allowing to form the slope of the roof. These trusses were mentioned before, as those built over diaphragmatic arches. Torres Balbás, who studied this building type, described these structures like, of fast construction, without the complexity and slowness that required the vaulted forms.[1] Also its use was advantageous since it allowed that the timber elements could be thinner, as the distance between its supports were reduced.[2]

Rafter trusses consist of the formation of a central support of two-faced elements that are higher than the outer ends, in order to form slopes. They lean in the central point forming the ridgepole ensuring stability within its plane each one of the trusses. The rafters produce thrusts in the walls on which they support. The walls must resist these thrusts, constructing walls of greater thickness, building abutments to prevent the lateral motion, or introducing tie-beams to the system. In these trusses, the tie beams do not correspond with the rafters, existing a fundamental element of transmission of the lateral thrust, that are

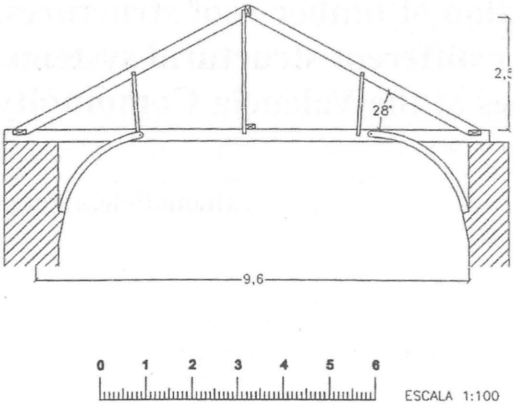

Figure 1

the wall-plates. On these elements they support the rafters, forming birdsmouth joints.

Rafters and tie beams that may incorporate also a king post and braces form the scissors brace trusses. This elementary triangle that was denominated as «scissors» by the Spanish authors of the c. XVII,[3] was already known by the Romans as describes Vitruvio in its Book IV, Chapter II.[4] He even relates that he has covered a basilica with that system, of 17,80 m width. Also we have archaeological knowledge that Romans knew the scarf-joint, as well as other types of joints and carvings, from the archaeological studies conducted in Pompeya and Herculano.[5]

These roof trusses have the thrusts balanced allowing a constructive solution in its supporting walls very different from the rafter trusses. In this case the support is made over the plates, while in the rafter trusses this element becomes necessary to form the support of the rafters, and to fix the tie beams simultaneously.

The different translations done during XVII and XVIII centuries of Alberti[6] and Palladio[7] treaties, caused that the scissors brace trusses became one of the most frequently structural systems adopted to support roof coverings. Also inspired the construction of timber trusses for great buildings as in the Sheldonian Theatre of Oxford, by Wren in 1663, similar to which proposes Palladio for the Theater Olympic of Vicenza. Proposals that also includes Benito Bails in his treaty[8] illustrating several of those type of trusses, like the one of the church of San Andrea of the Valley in Rome, and the one of the Great Theater of San Carlo in Naples.

Nevertheless, the triangle forms following the Roman model were not adapted to the accused slope used in the centre and north of Europe during the XIIth century. The first documentary references of these roofs we found in the medieval album of Villard de Honnecourt, perfectly detailed in his drawings.[9] Also we can see some of these medieval trusses of the French gothic style through the designs of Viollet-le-Duc.[10] These trusses can also be found in the historical English carpentry.[11]

There are also mixed structures that need of intermediate supports for the timber elements, to form the roof slopes. In these structures, not always special care was taken not to produce actions over the brick elements.

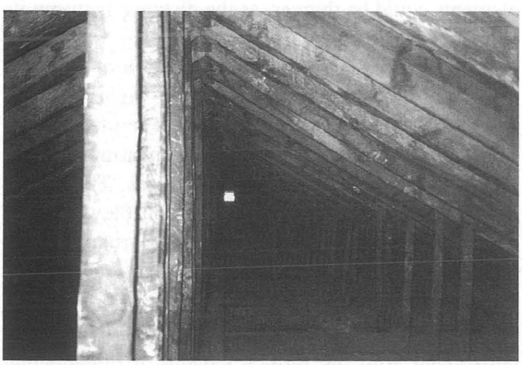

Figure 2

Figure 3

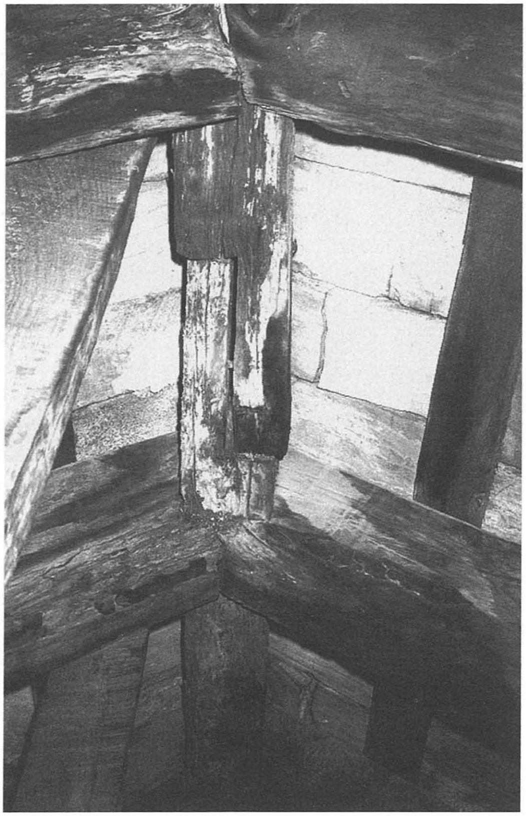

Figure 4

Therefore, there must be a direct relation between the structural form adopted for the timber truss and the configuration of the wall structure of the building.

The most stable form, the triangle trusses, when built over vaulted spaces, needs higher walls, in order to save the key of the vault. Rafter trusses need of some elements to avoid thrusts. Purlin trusses can only be laid over diaphragmatic walls, dividing the interior space in bays.

The way in which the roof trusses are built is inherent to the material, as it happens with most of the building materials used in construction. Timber elements used in construction entirely depend on its cross section and its length. When dimensions of length needed exceeds the one that can give us the available piece, the carpenter has to resort to the unions and joints. In the same way it happens when the carpenter has to put in relation several timber elements or parts of a structure, to build a truss.

The different joints are not conditioned by the different types of trusses described, but by the different efforts that the wooden elements have to transmit. In all the cases, the fact of making a joint supposes to make a cut in the pieces that are united, being created a weak point, which the carpenters have to diminish.

Availability of the material and use of timber construction at the Valencian Community

Timber used in historical building construction in this area have been varying, depending on the wood that was available in each place. The criteria of operation of the forests were not always based on economy, but in very diverse reasons. In fact, Europe was covered with forests, and has been men who made a way within them to obtain territories to cultivate or grass for the cattle that allowed its establishment.

The first types of timber construction were built with trunks, requiring a great ammount of wood.[12] They were constructed with softwoods that can give straight elements and of great length, aspects both of extreme importance in building construction. Hardwoods not always give straight elements, although for that reason was not less appreciated. It was mainly used disposed vertically, either forming elements of uniform section, or distancing the wood elements as posts. The intermediate spaces filled up

Figure 5

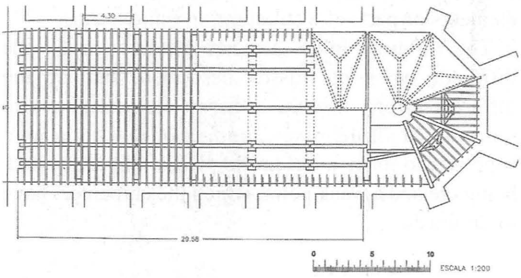

Figure 6

Figure 8

with other materials like clay or bricks, or also by means of wooden planks. Since this system allowed saving the material, it was the one that ended up prevailing.

When the operations of forests were made in an uncontrolled way, the constructors of cathedrals worried about it, because the distances they had to make to obtain adequate timber for that purpose employed a greater time.[13] Soon local resources were exhausted, and it was needed to bring timber from other sites getting to better prices. In fact, the wood coming from abroad was becoming a reality in the centre and the south of Europe, being mainly softwoods the wood employed for structural use.

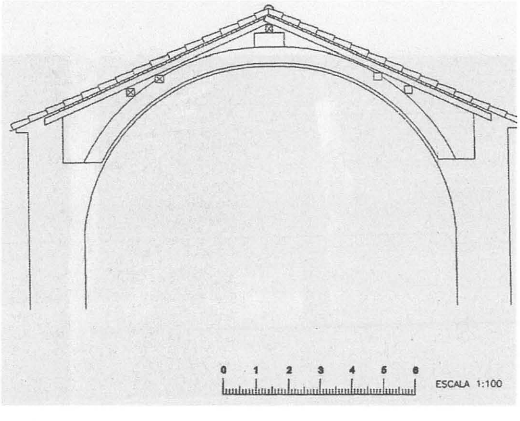

Figure 7

The great demand of wood for coal at the end of XVIIth century and for the construction of huge vessels, considerably reduced the reserves of forests. This affected to all Europe in general, and in a more serious way to those countries of great tradition of navigators and conquerors who needed great number of vessels.

The wood used for building construction in Spain has been basically obtained in the area where the building was built, coming from surrounding forests, arriving at the cities through rivers, or by sea through some next port.

The wood species used more in Valencia have been *pinus sylvestris* and *pinus halepensis* also called «pine from the river». This arrived at the city through the Turia River, *in rais* coming from the forests of the provinces of Teruel and Cuenca.[14] Sanchis Guarner[15] says that the wood used by the medieval carpenters, in XIV and XV centuries, coming from territories of the interior, had originated a powerful naval construction and an important industry of furniture.

The Xúquer River was used for wood transport in cities like Xàtiva and Gandía. In Alberique was the «*Vado de Barragà*», distant about 12 km to the city of Xàtiva, from where the wood arrived to be used in building construction.

It was from the XIXth century when «mobila « was imported from the United States with certain volume.

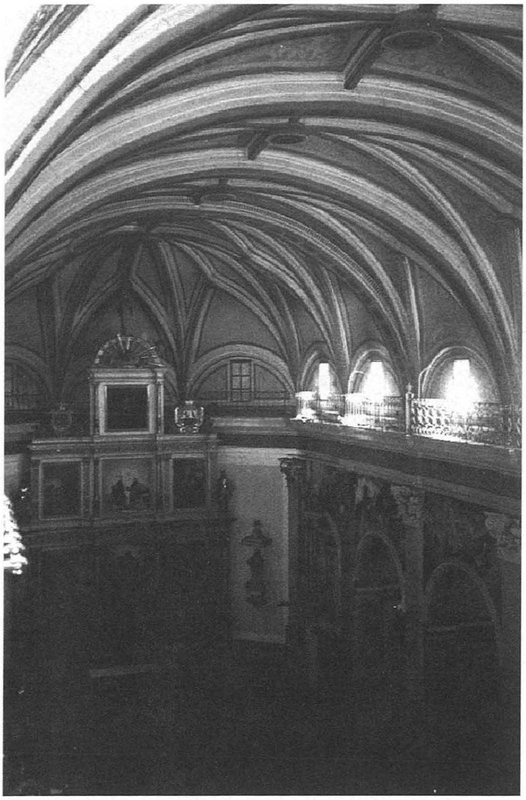

Figure 9

By this name there are identified five species coming from the south of the United States, from the port of Mobile,[16] in the Bay of the same name and next to the city of New Orleans. Between 1815 and 1861 this port reached his maximum splendour, with its exports of cotton and wood, fundamentally.

THE DESIGNERS

Trusses were built through specific rules based on the geometry, reaching their greater development towards the end of XVth century. All the treaties of architecture of XVII and XVIII centuries actually include knowledge of Arithmetic and Geometry like fundamental components of the architecture.

In carpentry and architecture treaties the layout of roof trusses are defined. Repeatedly it appears in the bibliography this detailed description about how to draw up trusses by means of triangles.[17] The Anglo-Saxons fundamentally use the squares for the design and layout of trusses, although in the Japanese carpentry there is also a tool that directly gives the dimensions of the elements to construct and form a truss. These systems are still used at the present time. Determination of the width and height were used to define the timber elements, based on proportions, thus defining all the elements that constitute the corresponding trusses and its joints. Once defined the slope, all steps followed to build the trusses were similar, in all methods.

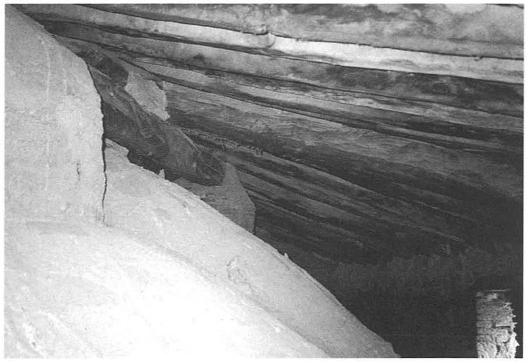

Figure 10

Carpenters to show the clients the idea they will develop in the future building frequently used models. Fray Andrés de San Miguel says that in case of doubt « . . . *and in works that they have difficulty*

Figure 11

Figure 12

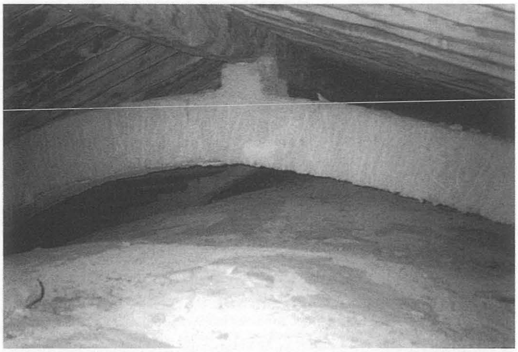

Figure 13

is accustomed to the most understood to make model than it is the same work in small, where they correct the defects and they are hazen better than in the work . . . ».[18]

The «*tracistas*» were master carpenters, master bricklayers or master masons. They were formed in geometry so that they were able to represent his idea, in drawings or models. They not only had to be formed in geometry, but, in addition, they had to know about the last architectonic forms and tendencies. They were who determined the slopes of the trusses, as well as the type of truss more suitable for each construction. The masers masons or master bricklayers, denominated «*pedrapiquer* « and «*obrer of villa* « respectively, they could be the «*master of the work*» when they directed it, and not necessary be its designer. By the way, a carpenter could be «tracista» or designer of altarpieces and roofs, and even of the complete building.[19]

Case studies

The case studies that are included in this article have been selected in such a way that they offer a variety of different solutions in relation to the wall structure We can try to to infer on those, who were the possible authors of their layout.

The selected cases talk about the different types of trusses before mentioned. Thus we have a rafter truss, like the one over the dormitories at Santa Clara Monastery, in Xàtiva, a purlin truss of the roof at the church in Albaida, and a scissor brace truss, the one over the Golden room, at the Palace of the Duc, in Gandía.

The roof structure of the dormitories at the convent for nuns of Santa Clara,[20] Xàtiva

The convent is in the street of Montcada at Xàtiva, next to the square of the Trinidad. Here another convent was located, the one of the Trinidad, that gave the name site, although this one no longer exists.

Fray Alberto Pina, Carmelite architect who resided and worked in Xàtiva in centuries XVII and XVIII, being director of the Colegiata of that city, wrote a «Description of the measures and magnificence in which it is constructed the real Monastery of very illustrious Nuns of Santa Clara in the city of San Felipe», that allows to know its configuration in those dates. It says that the monastery has four facades, one to the Montcada street (main facade), to the one of the Leon, and the convent of the Trinitarians monks.

Each side measured 343 Valencian handspans, by 74 of elevation. From the pointed arch access with battlements, we can reach the patio of entrance of the nuns, house keeper, door of the church, parlour, the dormitories of the nuns and the stairs to access to the door of the superior cloister. This piece is of starred vault and has 80 handspans.

According to that document, each cloister measured 208 handspans of length (about 47.32 meters) and 18 handspans of wide (4.095 m), and 28 handspans height (6.37 m). The cross vaults were

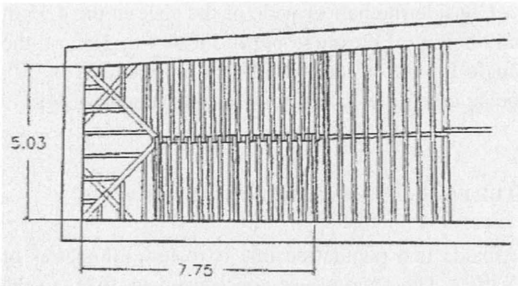

Figure 14

decorated with bosses. The dormitory of the community measured 116 handspans (26.39 m), of 40 of width (9.10 m) and 38 of height to its vault (8.65 m).

The superior cloister, to which was acceded by the door of the Virgin, did not have vaults, and agreed with those of the ground floor in its dimensions. The high closing was not gothic but renaissance, like the superior choir and chapter house. The church, of 110 handspans of length (25 m) by 38 of wide (8.65 m), had lateral chapels. It was reformed in XVII century, for the construction of the high and low choir, and renovation of finishing of the walls.

Damages caused by the 1748 earthquake

The city of Xàtiva underwent the 1748 earthquake, having its epicentre in that city. In a report on the damages caused by the 1748 earthquake we can read that « . . . some ruins in the cloister are recognised, particularly the one that noon light receives, leaning about three fingers, and the floor of the superior cloister, with some cracks, are seen going inwards the walls of the cells; that the pieces of the infirmary, the rooms, kitchen, common place, tower and noviciate, have leaning their walls and partitions; that in the choirs high and low where the large corbel that maintains one of the main beams was broken, a corner of them was opened and by the thirds of the arches it was breaking all the nave of the church, sacristy and parlour, opening vaults, arches and walls. And finally, the corner of the wall of the angle of the closing that is next to the door of the Leon, that before earthquakes already had a crack opened from above to down, has increased up to four fingers by the violence of the earthquake. But that, the referred ruins, admit safe repairs, like it has been made already in the wall that divides the dormitory of the common place, that it has been rebuilt from the foundation of the main wall; in the kitchen of the infirmary, that has been completely repaired, giving support to the tower, rooms noviciate, and common infirmary; in the walls of the church, that have been closed and joined with the greater firmness; in the bell tower, that already is strengthened its stairs and ends; in the chapter house where the arches with a pillar of five handspans have been filled up until receiving a third of the arch that it loads to the corner of the tower; and another one underneath the floor of the refectory of the infirmary, lying down the corresponding chains so that everything is left all the rest well joined and then that is recognised badly joined, can, with facility, to be applied the repairs corresponding to way that strengthens its security . . . ». Next, the report values the expenses of the repair in about 3,000 or 4,000 pesos.

It acted of witness for that report, the Carmelite architect Pina, who years before, in 1744 had made a report on the state of the «modern vaults and its tile roof» It said that after inspecting the vaults he appreciated that « . . . the roof structure that it loads on the pointed arches, without the requirements that the art requires, reason why must disarm all the tile roof demolishing the old arches and all the load of ashlars, jointing the new tile roof in scissor trusses or purlin trusses, tightened the four walls . . . ».

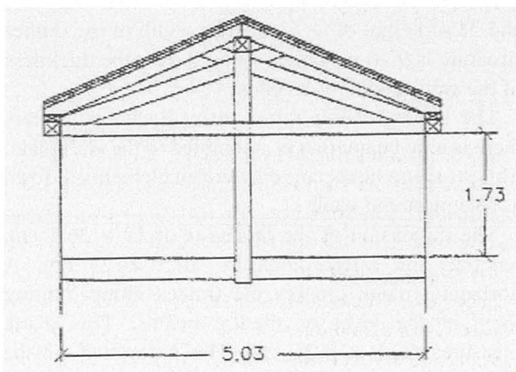

Figure 15

Figure 16

The timber trusses are on the church and the dormitories. We do not know if the dormitories are the original ones of the convent, described by the architect Pina, or if they were constructed after his intervention in it. He, given the state that presented after the earthquake, which we have described, also reformed the church. Both trusses we think that have been constructed by Fray Alberto Pina.

The convent it returned to be partially destroyed in the last war, having left very few original constructions: the church, the refectory and a dormitory constructed in century XVIII. Here we present the roof over the dormitories.

The roof truss over the dormitories

The aisle of the dormitories, according to the description of the architect Pina, measured 26.39 m long (116 handspans) by 9.10 m wide (40 handspans) and 38 of height of its vault. The width of the timber structure is 9.26 m, since it is built over the thickness of the wall, in one of its ends.

The structure is a rafter truss. Each two rafters there is a tie beam, that is assembled to the wall plate. This structure holds curved wooden elements to form a false plastered vault.

The dimension of the braces is of 12 × 26.5 cm, whereas the rafters measure 10.5 × 23 cm. A horizontal plank crosses the trusses along, uniting them at the level of the tie beams. This plank measures 0.11 × 0.21 cm. The separation of the rafters is of 0.69 m, whereas the one of the tie beams it is of 0.87 m.

Considering half of wide of the aisle in the 4,55 m and height of the ridge purlin located to 2.63 m, the angle formed by the rafters and tie beams is of 30º, being able to be drawn up with the triangle of 6.

The roof of the church at Albaida

Albaida is a population that is to few kilometres of Xàtiva. The church was constructed in 1621, in the centre of the villa. Next to the church one is the Palace of Marquise de Albaida, and the Abbey House, constructed in 1772 by the mentioned Marquise.

The church displays an interior with quadripartite vaults with tiercerons, and consists of five bays, plus the apse, that is of polygonal form, of five sides. The wide one of the nave is of 13.40 m, and its length of 40.80 m.

Figure 17

Due to the proximity with Xátiva, it is probable that the 1748 earthquake has affected the vaults, although the data has not been located to document this fact. In one of the little pillars that allow the disposition of the common purlin in the roof, there is a date, that of 1736, previous one to this earthquake, which allows to think that a total collapse of the structure did not take place.

The purlin truss of the church

The roof of the church is of two slopes, defining in the apse a polygonal form. The structure presents purlins as 1st order elements, being classified within this type of trusses.

The arches that divide the nave in bays, of 5 m of length (to axis), surpass the height of the brick vaults, allowing to support the common purlin on these. In the arches that separate the second and third bays, there are no such over-elevations, being necessary to supplement the height of these by means of small brick pillars.

The common purlins, therefore, rest on these small brick pillars built over the arches that divide in bays the nave. The ridge purlin, of great dimensions, (20 × 26 cm) is practically laid upon the keystones of the arches. The purlins, like the other elements that constitute the structure, are trunks decorticated with quite coarse squaring. These measure 25 × 24 cm and 23 × 27 cm. Over the purlins, there rafters, as elements of 2nd order, of variable section (of 10 × 19 cm, and 12 × 18 cm).

The roof of the apse is solved by means of a peculiar system that defines supports built over the vaults, although resting the small pillars on the nerves or stars or rosettes of the rib vaults, without affecting webs.

On that area were created two systems of supports, one displayed over the vaults, by means of small pillars on which they support common purlin. On these common purlin it arranges others that they are parallel to the sides of the polygon that defines the apse. On the first system of common purlin it locates the rafters that define the edges of the polygon. Smaller elements support them on the second system of common purlin.

In relation to its mechanical behaviour it is necessary to indicate that in this truss, the common purlins are deflecting because of the loads of the covering material, that gets by means of the elements from 2nd order to them. The common purlin, of 5 m of length, with sections of 24 × 25 cm, fulfil their resistant mission.

With respect to the solution given to the truss of the apse, the disposition of the architectonic elements in its design has considered, supporting elements of the roof where there were nerves of the inferior vault.

The Golden Gallery Roof. Palace of the Duc. Gandía

The «Golden Gallery», or «Obra Nueva», was built by D. Pascual of Borja in the last quarter of XVIIth century. There are five united halls to each other forming a gallery. These halls separate by means of

Figure 18

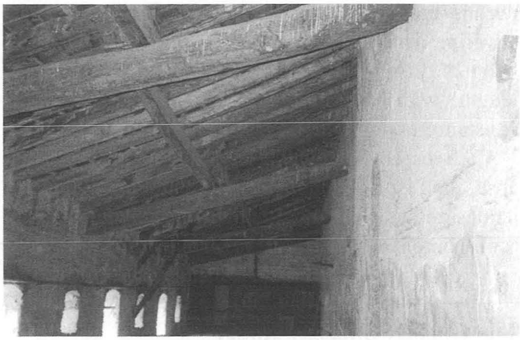

Figure 19

carved and golden polychrome wooden elements. It has 38 m of length, and it is at the western side of another room, the Green one.

The roof that we present in detail corresponds to the western extreme of the gallery, presenting a three sloped roof, in a length of 10 m. The rest of the Room has a roof structure made of rafters, to one slope, to the leaning to the patio of «Cañas».

This roof it is considered to be the original one of its construction, although some substitutions of their elements are appraised. The trusses are displayed at a height of about 2.40 m with respect to the coffered ceiling of the Golden Room.

It is braced scissors truss, formed by rafters crossed to support the ridge purlin, a tie beam that is assembled in wall plates, on which there stands the rafters. There is a great beam to a height of 80 cm on the ceiling of the Golden Room, that is related to the king post that it crosses all the height of the scissors, from the ridge purlin to form the support in this great beam. There are three of these scissors trusses, being the last one solved to procure the third slope of the roof.

The dimensions of the elements that constitute it are the following one: the pairs are of 14×21 cm, the brace of 17×21 cm, the inferior beam of 29×30 cm, and the kingpost of 22×26 cm. The rafters are assembled to each other with halved joint, and to the hip rafter; kingpost is assembled with half lap joint to the tie beam and the beam.

From the last two scissors start the hip rafters in the diagonals of the plan, to support the third slope, related together by means of struts. Over the hip rafters are disposed rafters, like small purlins.

The covering material has been recently treated against insect attack, and verified its watertightness.

The rest of the room displays a structure of rafters to solve the one slopped roof. Since the rafters have too much length, a support of beams disposed longitudinally to the room has been procured, resting over great beams that lays on the outer wall to the patio of Cañas and on the wall that separates this room to the next one.[21] These beams are distanced about 6 meters and they are not horizontal, presenting a small inclination, like the rafters, but with minor slope.

Conclusions

In all the studies cases carpenters and master builders knew how to complete the roof structures in the most accurate way in each building.

Carpenters had shared the knowledge of the office and applied them to these solutions. These masters extended it all around the world, obviously with the particularities that the different carpenters added to those.

The case studies of these buildings contributed to recover this knowledge, and can help to us to value them more accurately.

Notes

1. Torres Balbás, L., Naves de edificios anteriores al siglo XIII cubiertas con armaduras de madera sobre arcos transversales, *Archivo Español de Arte*, CSIC, Madrid, 1959, page 109 and s.s. y Torres Balbás, L., Naves de cubiertas con armadura de madera sobre arcos perpiaños a partir del siglo XIII, *Archivo Español de Arte*, CSIC, Madrid, 1960, page 19 and s.s.
2. Exist some very well conserved examples in the Valencian area. Recently the coffered ceiling of the church of Sant Pere at Xàtiva and the one of «la Sangre» at Lliria, both in the province of Valencia, and the one of Santa Maria in San Mateo, Castellón, have been repaired. A great number of buildings with this type of ceiling could be cited, like the churches of Santa Tecla and San Felix in Xàtiva, the church of «de la Sangre» in Onda, the chapel of the communion of the church of Godella, the church of the Cristo de La Paz, the church of El Salvador of Sagunto, the church of San Anton in Valencia, and the church of Santa Maria of Alzira. See Zaragozá Catalan, A., Naves de arcos diafragma y

techumbre de madera en la arquitectura civil valenciana, *Actas del I Congreso Nacional de la Construcción*, Ed. CEHOPU y ETSAM, Madrid, 1997. Page 551 and s.s. See also Zaragozà Catalán, A., *Arquitectura Gótica Valenciana*, Valencia, 2000.

3. Fray Laurencio de San Nicolás, *Arte y uso de la arquitectura*, Madrid, 1639 and 1664. Re-Edition Madrid 1989. Collection Juan de Herrera. It mentions the called scissor brace trusses talking about this type of structures.
4. In Book IV, Chapter II, we found a description of the form to construct the roofs: « . . . en todos los edificios se pone encima maderaje, a cuyas piezas solemos dar diferentes nombres, según son también sus usos diferentes. Maderos mayores, ó madres se llaman las jácenas o piezas que se sientan sobre las columnas,. Los de los altos quartones y tableros . . . » It continues saying that « . . . En la armadura del techo, si el espacio es muy grande, se ponen el madero del caballete en lo alto, llamando columen (de que tomaron nombre las columnas), los tirantes y los cabrios. Si el ancho es moderado, entra también el columen y los pares llamados cantérios, que vuelan fuera de la pared a formar el alero. Sobre dichos canterios, van las vigas o quartones llamados templos: y sobre éstos inmediatos a las tejas los listones llamados asseres, que también salen fuera de las paredes cuanto baste a protegerlas. Y en esta forma todas las cosas tienen su propio lugar, género y orden . . . ». Vitruvio, *Ten Books of Architecture*, translated by Jose Ortiz y Sanz, Madrid, 1787.
5. Adam, J. P., *Roman construction,* Ed. Los Oficios, Leon, 1996. Page 222 and s.s.
6. Alberti, L. B., *De re aedificatoria,* Florence 1485, translated by M. Alonso Gómez, 1582, Reedited by Ed. Albatros, 1977.
7. Palladio, A., *I Quattro Libri dell'Architettura*, Venice, 1570, Reedited by Ulrico Hoepli, Milano, 1968.
8. Bails, B., *De la arquitectura civil*, 1ª Edition 1783, Reedited Murcia 1983. Volume I, Critical Study, by Pedro Navascués Palacio.
9. Cuade*rno de Villard de Honnecourt*, Akal Editions, Madrid, 1991.
10. Bechmann, R., Los dibujos técnicos del Cuaderno de Villard de Honnecourt, *Cuaderno de . . .*, op. cit.
11. Viollet-le-Duc, *Dictionnaire Raisonné de l'Architecture*, Volume II, Paris, 1859.
12. Hewett, C., *English Hisotric Carpentry*, Ed Phillimore, Sussex, 1980, and «English Cathedral and Monastic Carpentry», 1985.
13. This building type has been used indifferently in the Scandinavian region, alpine zone and in North America. See Brunskill, R. W., *Timber building in England*, London, Ed. Víctor Gollancz, 1985, page 24.
14. Bechmann, R., *Les recines des cathedrales*, Ed. Payot, Paris, 1984. Page 93 and s.s.
15. There are references of the wood purchase coming from territories of the Marqués of Moya, in the Province of Cuenca, 1533, for the construction of the coffered ceiling of the Consulate of the Sea in the Market of Valencia. Aldana, S., *La Lonja de Valencia*, Valencia, page 55.
16. Sanchis Guarner, M., *La Ciutat de Valencia,* Main House of Valencia, Valencia, 1972. Third edition 1981, pages 175.
17. The port of Mobile depended in century XVI of the Spanish crown, and, in century XVII of the French. It was in 1780 when this port returned to depend on the Spaniards, until 1815.
18. See Nuere, E., *La carpintería de lazo. Lectura dibujada del manuscrito de Fray Andrés de San Miguel*, Colegio de Arquitectos de Málaga, Málaga, 1990; Mariátegui, E., *Breve compendio de la Carpintería de lo blanco y tratado de alarifes*, 1° Ed., 1867, Madrid, 1912.; Fray Laurencio de San Nicolás, *Arte y uso de la Arquitectura*, Capítulo XLVII, Trata de que fuerte se hayan de trazar las armaduras, y cuantas diferencias hay de ellas, Madrid, 1639 y 1664. Collection Juan de Herrera, Madrid 1989.
19. Nuere, E., *La carpintería de lazo*, op. cit., page 26.
20. In documents to contract the roof of the Sala Nova at the Palau of the Generalitat, end of XVIth century XVI, it was proposed to be given to «mestres architectors, pedrapiquers o altres qualsevol persones» Gómez Ferrer, M.*, Arquitectura en la Valencia del siglo XVI. El Hospital General y sus Artífices*, Ed. Albatros, 1998. Page 176.
21. The wife of Admiral Roger de Lauria, Doña Saurina de Entenza, founded the monastic house of the nuns on 1325.
22. This room is the one named «Sala de los Carroces & Centelles y de los Estados de Cerdeña».

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Masonry domes. Comparison between some solutions under no-tension hypothesis

Michele Paradiso
Marta Rapallini
Giacomo Tempesta

EIGHTEENTH-CENTURY «MEMOIRES»: FIRST INTUITIONS OF TWO-DIMENSIONAL BEHAVIOUR

The first work that it is concerned with equilibrium problem of vaults and domes dates back to May 19th 1734; the author of this work was the mathematician Pierre Bouguer (Bouguer 1734). Also being the first author to be concerned with the subject Bouguer's treatment of the problem contains, even if only in qualitative way, the consideration of the main characteristic of the behaviour of these structures: the two-dimensionality. In practical Bouguer realizes that the behaviour of the structure cannot be always reduced to a series of arches approached each other, but a transmission of stresses also along the parallels of the solid of revolution exists.

The author deals with the two characteristic topics of the problem: the search of the geometry shape of the vault with an assigned thickness and the dual case in which, in case that the lower surface curve is assigned, the aim is to determine the variation of the thickness.

In commenting on the various types of suggested meridian curvature (conical domes, conical vaults and spire vaults), Bouguer asserts that the resultant of the actions transmitted from the upper part of the vault can intercept the joint of interface with a non orthogonal angle. This hypothesis, added to the absence of friction one, coincides with the statement that the stability of the structure depends not only on interactions along the meridian line, but also along the parallel line. In fact Bouguer writes that if the resultant of the actions transmitted from the upper part of the vault intercepts the joint of interface with an angle that points out the tendency of the voussoir to slip towards the inside of the dome «& c'est ce qui ne peut point arriver, puisque tous les autres Voussoirs de la méme assise s'y opposent, en faisant un égal effort» (Bouguer 1734, 150).

An analogous statement can also be found, nearly one hundred years after, in the treaty of Venturoli: «Perché se quella risultante declina piegando verso l'asse (il concio) tenderà a sdrucciolare in giù; ma

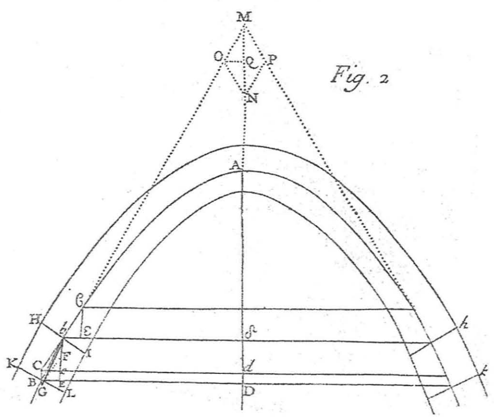

Figure 1
The Bouguer's dome

essendo la stessa tendenza in tutte le altre unghie che le stanno attorno per tutto il giro della cupola ed esercitandosi questa tendenza da tutte nello stesso tempo e con forza uguale, ben si vede che tali sforzi s'impediscono e si elidono l'un l'altro, né possono avere l'effetto per cui la cupola si dissolva». (Venturoli [1806] 1833, 205).

In dealing with the determination of the generatrix line of a revolution dome with the concavity turned towards the revolution axis, the author expresses the solution by means of a famous inequality that translates the necessity that, in any point, the tangent to the curvilinear axis of the dome, in order to prevent that the voussoir is expelled outside, needs to be smaller than the angular coefficient of the line thrust in that point. Using Bouguer's notation:

$$CG \geq CB \tag{1}$$

The inequality (1) expresses the relationship between the funicular curve related to the loads and the searched geometrical axe of the revolution dome. With reference to Figure 1 let us indicate the axis AD with x and the axis BD with y, in a modern notation Bouguer's inequality becomes (Rapallini 1994):

$$\frac{\partial H}{dx} = \frac{y\sqrt{1+x'^2}}{x''} - \int y\sqrt{1+x'^2}\,dy \geq 0 \tag{2}$$

where function x expresses the equation of the curve of the meridian line of the dome and where the thrust H of the dome is equal to:

$$H = \frac{\int y\sqrt{1+x'^2}\,dy}{x'} \tag{3}$$

Therefore the Bouguer's condition, based on purely geometrical considerations, corresponds to the analytical equation expressing the fact that the thrust of the dome, for obtaining an equilibrated solution, must be not decreasing function (Rapallini and Tempesta 1998).

In the case in which x represents the unknown of the problem, $H'(x) = 0$ determines the shape of the revolution dome in which the circumferential stresses are everywhere null, that is the surface generated from the revolution of a not homogenous catenary or, as Bouguer says, the «*derniére de toutes*» (Bouguer 1734, 152); $H'(x) > 0$ expresses instead the shape of the revolution dome in which the circumferential stresses are everywhere in compression. In the case in which x represents the equation of the circumference, $H'(x)$ is the equation of the curve named «strofoid» (Eddy 1878, 54) which defines the variation of the horizontal component of the tangents to the dome. The point corresponding to null values of the circumferential stresses coincides with the maximum of the strofoid curve.

The first application proposed from Bouguer is the verification for the equilibrium and the admissibility of the state of stress in the case of semispherical dome with constant thickness. If a is the radius of the sphere the inequality (1) becomes:

$$y^2\sqrt{a^2-y^2} \geq a^3 - a^2\sqrt{a^2-y^2} \tag{4}$$

from which it is obtained:

$$a\sqrt{-\frac{1}{2}+\sqrt{\frac{5}{4}}} \geq y \tag{4}$$

Considering $y = a \sin\alpha$ (where α is the angle that denotes wideness of the cap) the spherical vaults are in equilibrium without not admissible circumferential stresses if $\sin\alpha \leq 0.78615$, from which $\alpha \leq 51°\ 49'$. This value of α represents just the parallel of reversal sign of the circumferential stresses, as it is easily verifiable applying the equations of equilibrium of the shells in membrane regimen.[1]

Bouguer supplies an approximate solution of the problem by means of integration by series:

$$x = \frac{y^3}{6a} + \frac{y^7}{336a^3} + \frac{y^{11}}{42240a^5} + \\ + \frac{y^{15}}{9676800a^7} + \frac{y^{19}}{353009640a^9} + \ldots \tag{5}$$

The previous expression obtained represents the shape that must have the medium line of an isolated slice of dome so that it is in equilibrium if just subject to self weight.

The same solution to the equilibrium problem of a masonry dome will be proposed in following works during the same century: from abbot Bossut (Bossut

1774, Bossut 1778), from Mascheroni «Questa equazione scioglierebbe il problema della curvatura d'un velo lento attaccato ad un cerchio orizzontale, che senza rughe si disponesse nella forma di un catino» (Mascheroni 1785, 86), from Giuseppe Venturoli in his treaty of the early of nineteenth century (Venturoli [1806] 1833). The model from which the searches start is the same: the dome as a monodimensional structural system. The studied problem is that one of the *figure* to give to a curve from the revolution of which a dome can be obtained that is equilibrium without contribution of friction and of the stresses acting along the parallels: all the authors reach the same equation of the not homogenous catenary.

Nineteenth-twentieth century formulations, that is the monodimensional analysis of the masonry domes within the limit analysis

The purely monodimensional eighteenth-century vision of the dome diminishes with the widening of the nineteenth-century studies in matter. The relationship between the problem of a dome and the problem of membranes seems obvious already rather although much time must pass before still that a corrected general theory is reached; it will be only provided a century later from Beltrami (Beltrami 1882).

The membrane analysis can be used also in the case of domes built in masonry material which, as is well known, is provided with mechanical characteristics that differentiate it in substantial way from the standard material. In fact if in a masonry dome the thickness is thin in comparison with the span and if a no-tension hypothesis for the material is assumed, the bending behaviour become can be neglected because incompatible with the mechanical characteristics of the material.

Nevertheless the no-tension hypothesis does not permit to accept tensile stresses in the structure, therefore it is necessary to introduce at least some limitations in the sign of the stresses: this is, as an example, Schwedler's approach (Schwedler 1851). Schwedler, around to the half of the nineteenth-century, proposes in fact a graphical method for the determination of the state of stress in a dome. After all such a method translates, in graphical shape, the solution that can be obtained from the equations of equilibrium in membrane regimen, making easier the solution in the case in which the shape of the dome is not regular (Santarella 1972, 2: 672–679).

In the case we analyse a masonry dome it is suggested not to consider the tensile forces acting on the lower parallels; the pressures exerted may be obtained by the polar radii drawn from the last pole of the polygon.

This method involves the identification of two parts of the dome that have a different behaviour, starting from the point in which the circumferential stress becomes zero, which is obtained through the solution of the problem of the membrane equilibrium equations. In this case, we then accept the coincidence between the geometrical axis of the structure and the surface of stress of that part of dome in which we have a bi-dimensional stress state; the axis changes only in the second tract where the parallels would result stretched.

It is worth noticing that, for the hypothesis chosen, in this tract we can usually observe the curve of stress coming out of the outline of the dome that is the object of verification; in-fact in this method no further condition is imposed on the thrust line of the second tract.

It is also possible to propose another approach to the problem, considering that the reacting structure, i.e. the shape of the thrust surface, is the main

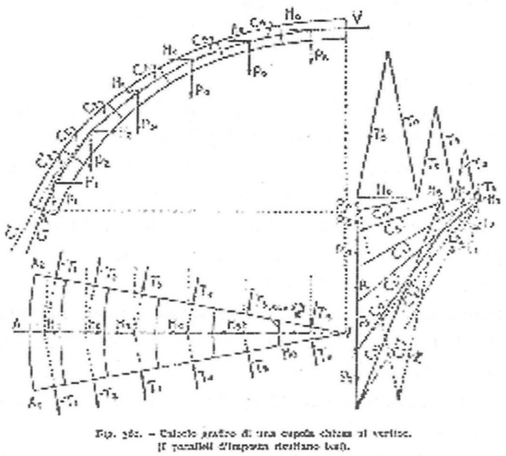

Figure 2
The graphical construction of the Schwedler method

unknown element of the problem.[2] Only by discarding the hypothesis that the thrust curve has to coincide with the axis of the structure (hypothesis at the base of membrane solution), we can effectively describe the behaviour of a masonry structure.

The proposed methods for the finding solution must give evidence of two opposite phenomena which are present in the masonry existing domes.

We are referring to the fact that the spherical masonry domes get damaged along the meridians without any construction defect of stability; and on the contrary, there are masonry domes that present no damages in those areas in which the parallels are stretched.

In 1742, a committee was formed to study the causes related to the instability of the dome of Saint Peter, that had been seriously damaged along the meridians. The committee, formed by three mathematicians, after a careful investigation of the failure pattern in progress, hypothesized that the collapsing mechanism accounted for the independence of the various dome lunes (Le Suer et al. 1742).

It was therefore discovered that the disassembly originated from a mechanism of rigid materials involving not only the vault, but the whole structural supporting system.

This way of studying the masonry behaviour anticipates, in a way, what will later be the application of the limit analysis of masonry structures, recently set up by J. Heyman. The solutions that Heyman (1967) and Oppenheim (1989) proposed, which were both obtained from the context of the limit analysis, are in fact based on the hypothesis that there is no hoop stress resultant among the contiguous lunes of the dome. What is hypothesized, is therefore a one-dimensional behaviour: «A convenient way to construct an equilibrium solution for the dome is to divide it into a large number of *"orange slices"* or lunes» (Heyman 1977, 108). So it is possible to use the «safe theorem», which states that the dome, or the slice that represents the dome, is stable if it is possible to define any thrust curve within the thickness. In the reduction of the problem to a monodimensional one it is evident the reference to the eighteen-century model, in particular the relationship between the *settore solido* of Poleni and the l'*orange slice* of Heyman (1965, 36).

Under these assumptions, the test of the dome stability is obtained through a comparison between the funicular of the loads which operate on a lune and the part of the dome itself. This method presupposes that the reacting structure is unknown in the whole section. Oppenheim, in the wake of Heyman, suggests, as a solution to the problem of an ogival masonry dome, the comparison between the shape of the funicular meridian (catenoid) and the part of the dome lune that we want to verify.

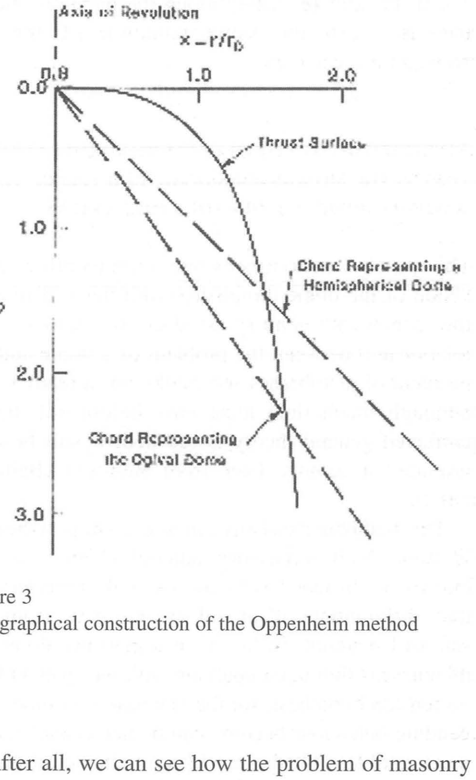

Figure 3
The graphical construction of the Oppenheim method

After all, we can see how the problem of masonry domes has been dealt with in accordance with two substantially different approaches: we have either considered the two-dimensional state of tension, that is, without introducing the thrust line among the unknown factors of the problem (Schwedler), or we have considered the unknown reacting structure hypothesizing a one-dimensional stress in the dome (first Poleni and the Three Mathematicians, afterwards Heyman in the environment of the limit analysis).

The recovery of the circumferential stresses: the originality of the nineteeth-century contribuitions of Eddy and Lévy

First H. T. Eddy, M. Lévy later, deal with the masonry dome problem separately by the standard material dome (metallic dome). Eddy in the introduction of his book points out: « . . . and in particular, it is believed that the dome of masonry is here investigated correctly for the first time, and the proper distinctions pointed out between it and the dome of metal». (Eddy 1878, vi).

The solution proposed by Eddy for the first time, and also explained by Lévy, is entirely obtained through means that are typical of graphical statics.

The original idea is to consider masonry as a no tension material, thus accepting the fact that the circumferential stress would result neutral in those areas where tensile stress would develop, and at the same time, to consider the two-dimensionality of the state of tension typical of double curvature structures such as domes, where this turns out to be compatible. These assumptions are explained by the fact that usually a dome displays two kinds of behaviour: one corresponding to the portions of the cup where there are compressive stress both along the meridians and the parallels; the other relative to the parts where the parallels are stretched: in this case we must assume that the stress is taking place only along the meridians.

This fact was intuitively pointed out by Bouguer (Bouguer 1734) and Venturoli (Venturoli [1806] 1833), when they accepted that the load resultant of the superior part of the dome may arrive more inclined towards the axis of the dome with respect to the normal to the joint bed.

From this approach it arises the fact that the reacting structure is one of the unknown elements of the problem, which is typical in the analysis of masonry structures.

The double behaviour was already hypothesized by Schwedler's solution: in this case we accept the result that the membrane equilibrium equations provide up to the inversion parallel; Lévy and Eddy, on the other hand, introduce some hypotheses that modify the overall solution.

In a masonry dome, to the uncertainty of the funicular curve relative to the part of the cup in which the parallels are subjected to tensile stress, it is added the position of the point where we have the crossing between the two different behaviours, « . . . the point where the hoop compression vanishes . . . » (Eddy 1878, 55) and the *point neutre* of Lévy (Lévy 1888, 43).

The dome therefore has to be considered separated into two parts: in the upper cup the funicular curve is represented by the entanglement of the tangents to the extrados of the third middle of the dome; in the lower part, the funicular curve passes through the extrados of the third middle of the dome over to the impost (as a hypothesis) and has a side which coincides with an unknown straight line tangent to the extrados of the third middle in a point of the dome that has to be determined, which is precisely the *point neutre* that Lévy refers to. The required condition, from an analytical point of view, can be formulated through the condition equality of the thrusts that are relative to the two parts of the dome at the point in which they connect.

The method of Eddy-Lévy

The analysis of the metallic dome is lead by Eddy by a graphical procedure which is based on the construction of the *st* curve [H′(*x*)], in Figure 4, which allows us to

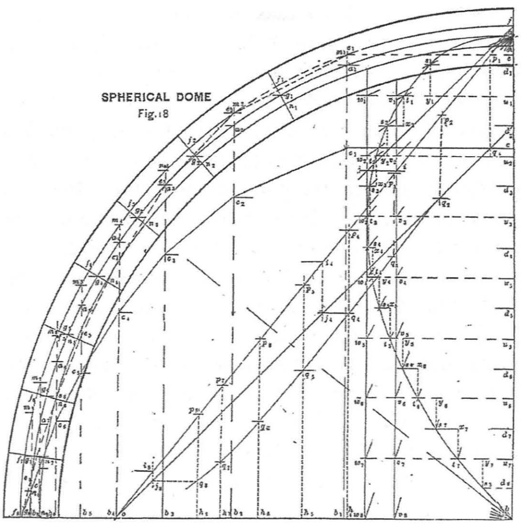

Figure 4
The Eddy's dome

determine the stress state referred to the middle surface. In the emispherical dome with constant thickness this curve is named strofoid and has equation:

$$\frac{y^2}{x^2} = \frac{r - x}{r + x} \qquad (6)$$

where r is the radius of the sphere.

The curve shows that the point which corresponds to the zero circumferential stress coincides with the point in which the strofoid achieve his maximum value.

In fact tracing a vertical straight line tangent to the strofoid we may verify that the contact point is identified by the angle ϕ = 51,8273° (ϕ = 0 in the vertex of the dome) and represents the point in which the circumferential stress vanishes. This result coincides exactly with the analytical solution of the system of equations which governs the membrane equilibrium problem of a shell.

About masonry domes, Eddy gives interesting considerations. For the first time it is stated that the thrust surface of a masonry dome of large thickness doesn't coincide with the middle surface, i.e. the shape of the structure is considered one of the unknown of the problem.

The Eddy's graphical solution requires the drawing of a tentative funicular polygon. The conditions are: polar distance equal to the maximum thrust of the spherical dome and it has to pass for the extrados point of the middle third at the dome base. Afterwards Eddy adds: «Below the point where the compression vanishes we shall not assume that the bond of masonry is such that it can resist the hoop tension which is developed. The upper part of the dome will be then carried by the parts of the lunes below this point by their united action as a series of masonry arches standing side by side» (Eddy 1878, 57).

It may noticed that the curve *cc* so drawn «falls within the curve of the dome, which signifies that the dome will not exert so great thrust as assumed» (Eddy 1878, 57). So the problem becomes to choose the conditions to draw a curve within the thickness of the dome. In this case Eddy proposes to apply the principle of the least resistance of Moseley (Moseley 1843, 10) and writes: «By the principle of the least resistance, no greater horizontal thrust will be called into action than is necessary cause the dome to stand, if stability is possible» (Eddy 1878, 57).

This principle is adopted by Eddy to express an equilibrium condition between two parts with different behaviour. The graphical solution requests the determination of a point belonging to the extrados of the middle third of the dome section in which the tangent to the circumference coincides with the polygon's side passing throw that point and throw the extrados point of the base of the dome.

Analytically the solution may be obtained by finding the intersection point between the function H_1 which expresses the thrust of the upper part of the dome, and the function H_2 which expresses the thrust of the lower slice (Rapallini and Tempesta 1998). The function H_2 is obtained by the intersection between the central axis of the system force representing the voussoirs's weight, the generic line tangent to the circumference and the last side of the funicular polygon passing through the assigned point at the spring, Figure 5.

$$\begin{aligned} H_1(\varphi) &= \frac{R^2(1 - \cos\varphi)}{\tan\varphi} \\ H_2(\varphi) &= \frac{R^2 \cos\varphi\,(d - R_e)}{[-R_e \cos\varphi + \tan\varphi\,(d - R_e \sin\varphi) - \tan\varphi\,(d - R_e)]} \end{aligned} \qquad (7)$$

The method of Eddy-Lévy better expresses, among the remembered contribuitions, the behaviour of a masonry dome and so his stability. In fact this method allows us to obtain a solution admissible in every part of the dome which takes into account the two

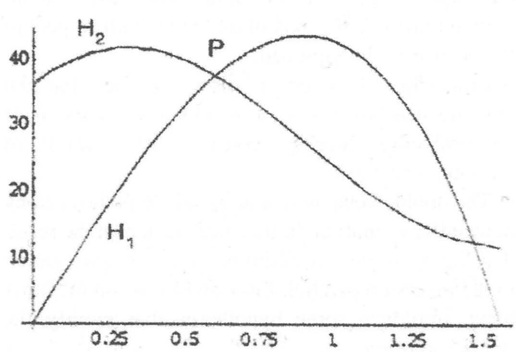

Figure 5
Graphics of the curves which represent the functions H_1 and H_2

behaviours, monodimensional and two-dimensional, from the beginning of the analysis.

THE TWO-DIMENSIONAL BEHAVIOUR OF A MASONRY DOME: A NUMERICAL PROCESS BASED ON A RIGID BLOCK MODEL

The basic characteristics of the presented model (Briccoli Bati et al. 1992; Pieroni 2000) allow us to relate the analysis of masonry to a unilateral contact problem among rigid block. In this sense the no-tension behavior of the material is concentrated totally in the contact joints between the elements. Those elements are supposed being rigid and they may suffer relative detaching and sliding along the joints. The model of the interface devices has a rigid-cracking behaviour and is obtained by a certain number of ideal unilateral bar. The interface device consists of normal bar to the interface and are capable of transmitting only compressive forces between the blocks, and additional bar, parallel to the interface, through which the shear forces can be transmitted, Figure 6. These bars are active only if the normal to interface device is active.

In order to find the unknown reacting structure, it is necessary to solve a non-linear problem.

Let us consider the general problem of a masonry structure consisting of n rigid blocks linked through m unilateral rigid contact interfaces. Assuming that the structure is subjected to the action of external load represented by F and to the influence of external inelastic displacements stated represented by Δ, imposing the equilibrium and the elastic-kinematical conditions related to the geometrical configuration at the generic step, the system of equations and inequalities that govern the problem, can be written in the following form:

$$\begin{cases} AX = F \\ A^T x = \Delta_1 + \Delta_2 \end{cases} \tag{8}$$

$$\text{sub} \quad \begin{matrix} X \leq 0 \\ \Delta_2 \leq 0 \end{matrix} \tag{9}$$

where A is the geometrical configuration matrix, X indicates the unknown vector of internal forces in the contact joints. The components of the unknown vector x represent the displacements of the centroids of the blocks; Δ_1 represents the vector whose components are external inelastic displacements; Δ_2 indicates the unknown vector whose components are «distorsions» which need to be defined in order to obtain a solution capable of satisfying both the equilibrium equations, while respecting the sign conditions, and the kinematical compatibility of the problem.

The general solution of the problem is $X = X_0 + X_N$ where X_0 represents an initial solution and X_N represents the particular solution we have to impose to respect the sign conditions:

$$\begin{aligned} X_0 &= A^T(AA^T)^{-1} F + (I - A^T(AA^T)^{-1} A)\Delta_1 \\ X_N &= (I - A^T (AA^T)^{-1} A)\Delta_2 \end{aligned} \tag{10}$$

Masonry domes may be considered like structures made by rigid blocks with no-tension interfaces, i.e.

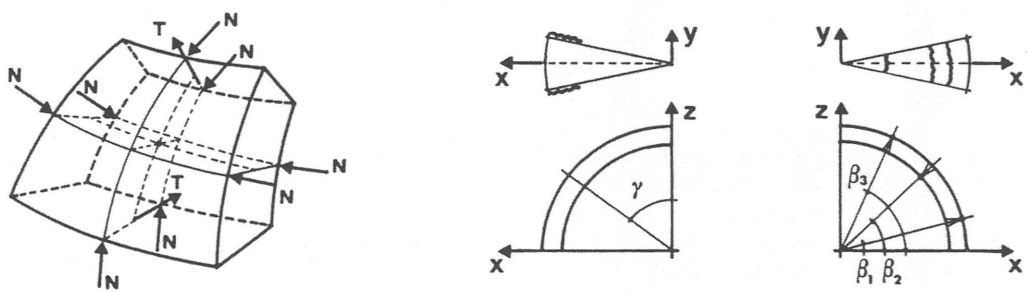

Figure 6
The rigid block of the numerical model (Briccoli Bati et al. 1993)

rigid-cracking, each of them delimited by two parallel arches and by two meridional arches. In Figure 6 it is sketched one of these elements. Every block is characterized by ten unknowns which can be found by solving systems (8) and (9).

The solution we obtain applying this method, if it exists, is admissible everywhere; furthermore the solution doesn't ignore the circumferential stresses, but consider them when they are present.

THE STUDY OF THE MASONRY DOME OF SAN BIAGIO AT MONTEPULCIANO ACCORDING TO THE PROPOSED METHODS

The works to build the San Biagio Church in Montepulciano (Italy) began on 1518 according to the project of Antonio da Sangallo il Vecchio. The architect choose the Greek cross for the plan of the church, being in the same wavelength with the great number of central plan buildings surmounted by domes and dedicated to Madonna which arose in Italy between XIII and XIV century.

In the center of the cruciform plan rises the impressive cylindrical timber structure, 10.17 m tall and decorated by sixteen single lancet windows, only four of which are open. The timber is surmounted by a dome on which vertex arises a lantern, how it is shown in Figure7.

The extrados dome of the San Biagio church presents a very rised curve. The extrados and intrados profiles may be approximated by two different arcs of circle whose centers are posed in different levels. Both of them have the same curve how is clearly showed in the tracing of Giorgi (Giorgi 1999).

For the mechanical analysis we refer to the tracing of Giorgi taking into account the dome with variable thickness. The thickness grows from 0.52 m in the keystone to 1.20 m at the springs, i.e. 8 cm. less than the total thickness of the dome, in order to take into account a non collaborative covering of such dimension.

We propose to verify the stability of this structure by applying the presented methods. The first model is the one of Heyman, i.e. of the limit analysis, where the dome is considered the as made by separated slices.

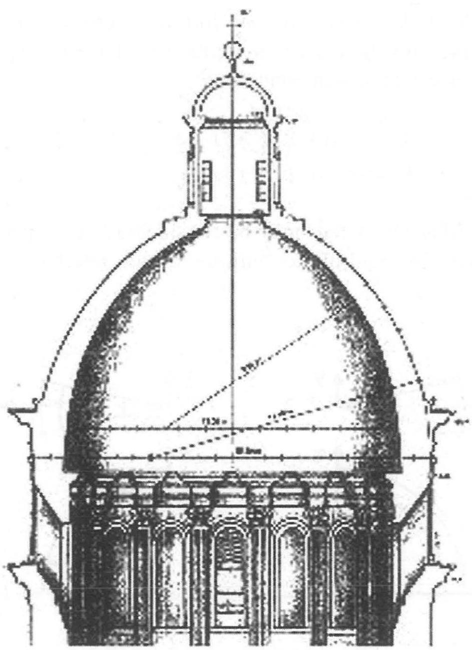

Figure 7
The cross section of the S. Biagio dome (Giorgi 1999)

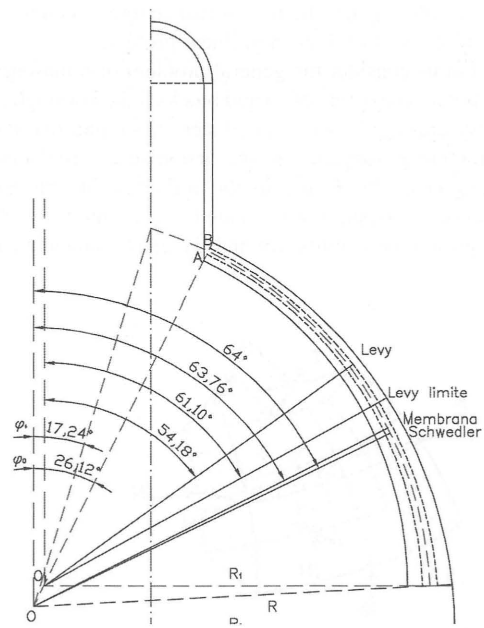

Figure 8
The scheme of the cross section of S. Biagio dome

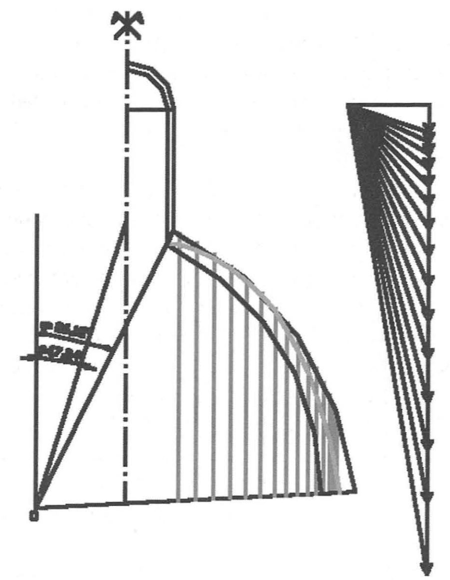

Figure 9
S. Biagio dome: the limit analysis by Heyman hypotheses (Lascialfari 2002, Tab. I)

So we have applied the Eddy-Lévy procedure referring it to the middle third of the section and extending it to the all section. Those authors consider since the beginning the double behaviour of the masonry dome.

Another solving method based on a double behaviour is the one of Schwedler.

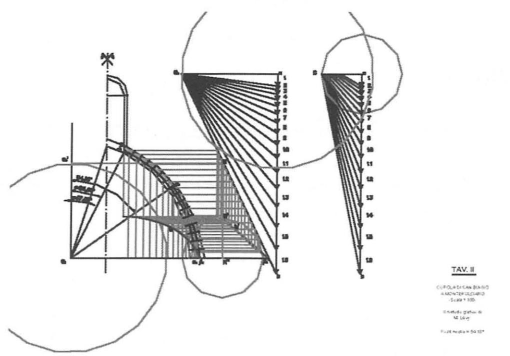

Figure 10
S. Biagio dome: the Lévy graphical method (Lascialfari 2002, Tab. II)

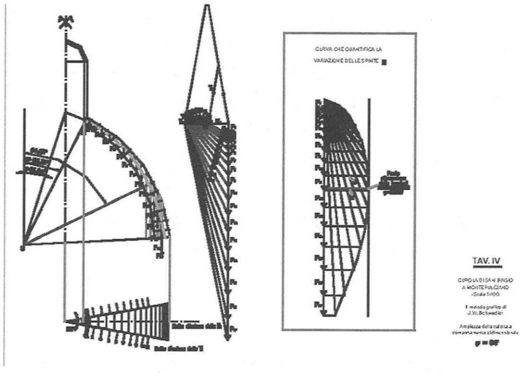

Figure 11
S. Biagio dome:the Schwedler graphical method (Lascialfari 2002, Tab. IV)

At least we have applied the membrane equilibrium equations considering the standard behaviour material. In the Figure 12 we have shown the values of the membrane forces along meridional lines and parallels line.

Final remarks

The Figure 13 shows a synoptic picture of the obtained results. It may be noticed that as the behavioural structure hypotheses decrease, and the admissible solution becomes consequently impossible, the portion of the dome subjected to a double compressive stress increases its width.

In fact the maximum width may be obtained by the membrane equilibrium equations: the point of the change of sign in the circumferential stress is at 63.76° from the crown.

In the Lévy method the neutral point, i.e. the point in which circumferential stresses vanish and under which the solution was obtained by a conditioned funicular polygon, is posed at 54.18° from the crown. Referring the Lévy method to the limit analysis, i.e. considering the solution admissible within the entire section of the dome, the neutral point lowers and arrive at 61.10°. It may be noticed that the Schwedler solution relative to the portion underneath the neutral point, which is at 63.76°, i.e. the position of the point in the membrane solution, is admissible also if it is

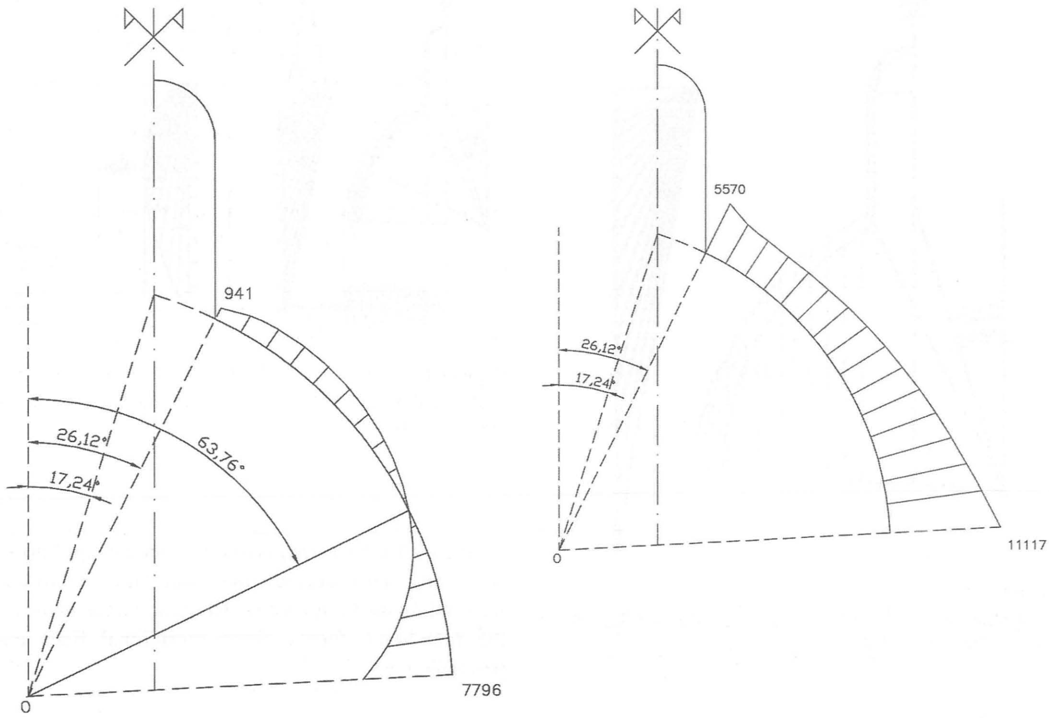

Figure 12
Biagio dome: membrane force diagram (Lascialfari 2002, 159)

not possible to impose any condition to the funicular polygon in this portion of the dome.

The limit analysis applied to a dome slice, i.e. according to the more restrictive hypothesis on the structural behaviour, gives an admissible solution also if the thrust line is tangent to the extrados in the upper part of the dome, Figure 9. Consequently all the other solutions are admissible but cause a stress pattern less hard for the structure.

The solution obtained by applying the rigid block model gives a solution near to the Lévy limit method concerning the position of the neutral point, but it is different in the drawing of the polygon of the upper part. In fact in this method the thrust surface isn't forced to coincide with the middle third extrados in the upper part, but it considers, if they are present, the effective compressive circumferential stresses. The solution will be so entirely admissible in the no-tension hypothesis for the material, according to the Heyman hypothesis, but it doesn't neglect the parallel contributions where they are compressive stressed.

Notes

1. For the membrane equilibrium equation see for example Flugge (1962).
2. Regarding this topic you may read chapter «building and structure» in Di Pasquale (1996).

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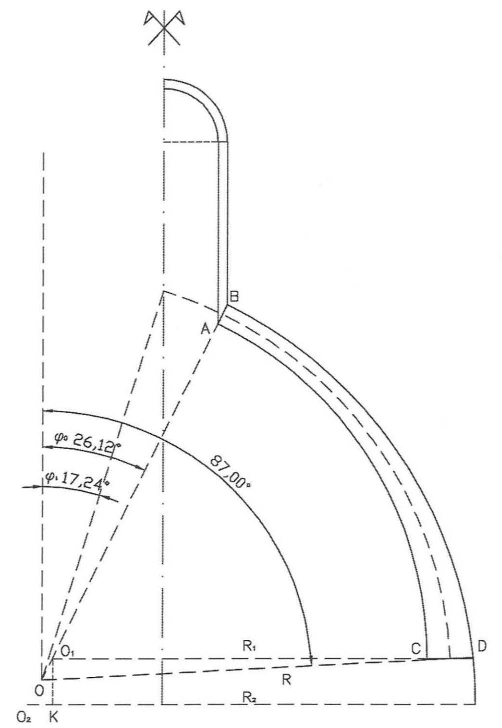

Figure 13
S. Biagio dome: comparison between the proposed methods. (Lascialfari 2002, 161)

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On the mechanics of segmental beams

H. Parland
A. Miettinen

The paper presents an extension of the classical theory of bending and compression of beams developed in the 19th century. This extension goes back to an earlier development of structural mechanics: starting from the 17th century (Derand 1643; La Hire 1679) the mechanics of rigid body assemblages were further developed during the 18th century (Poleni 1748; Coulomb 1713) and brought to its perfection in the 19th century (Poncelet 1822; Cremona 1872). The theory of voussoir arches and corresponding domes was purely geometric and its development was closely connected with that of the projective geometry (Derand 1639; La Hire 172**?**). A late intermediate link provided, finally, the mechanics of elastic contact initiated by Hertz (1881).

The purpose of this paper is to present a case study how the two directions, the geometrical one of rigid body assemblages and that of classical elasticity are united into a synthesis.

The nonmonolithic elastic beam

We consider an elastic cylindrical beam devided by cross-sectional joints into segments. The dimensions of the beam are: length L, cross section A with centroid axis x, principal axes y and z and corresponding second moments I_y and I_z, respectively. The external forces $p^*(\Gamma_e)$ acting on the external surface Γ_e including the endfaces $A(-L/2)$ and $A(L/2)$ induce in the beam a normal force $N(x)$, shear forces $Q_y(x)$, $Q_z(x)$ and moments $M_x(x)$, $M_y(x)$, $M_z(x)$ defined by the cross sectional stresses σ_x, τ_{xy}, τ_{xz}, respectively

$$\begin{aligned} &N(x) = \int_{A(x)} \sigma_x \mathrm{d}A\ ; \qquad Q_y(x) = \int_{A(x)} \tau_{xy} \mathrm{d}A\ ; \\ &Q_z(x) = \int_{A(x)} = \tau_{xz} \mathrm{d}A \\ &M_y(x) = \int_{A(x)} \sigma_x z \mathrm{d}A\ ; \qquad M_z(x) = -\int_{A(x)} \sigma_x y \mathrm{d}A \end{aligned} \tag{1}$$

which satisfy the equilibrium conditions at every cross section $A(x)$

$$\begin{aligned} &\mathrm{d}N(x)/\mathrm{d}x = -p_x(x)\ ; \qquad \mathrm{d}M_y(x)/\mathrm{d}x = Q_z(x)\ ; \\ &\mathrm{d}M_z(x)/\mathrm{d}x = -Q_y(x) \\ &\mathrm{d}Q_y(x)/\mathrm{d}x = -p_y(x)\ ; \qquad \mathrm{d}Q_z(x)/\mathrm{d}x = -p_z(x) \end{aligned} \tag{2}$$

where p_x, p_y, p_z are load components per unit length.

At the cross sections $A_\nu(x_\nu)$ of the dry joints, the stress vectors $\mathbf{p}_{\nu-1,\nu}(y,z) = \sigma_x\ \mathbf{i} + \tau_{xy}\ \mathbf{j} + \tau_{xz}\ \mathbf{k} = -\mathbf{p}_{\nu,\nu-1}(y,z)$ are subjected to the constraint

$$\sigma_x \leq 0 \tag{3}$$

These cross sections $A_\nu(x_\nu)$ divide the beam into segments (1) . . . (ν) . . . Within each segment (ν) there applies for the displacements $\{u_i\}$, the strains $\{\varepsilon_{ij}\}$ and the stresses $\{\sigma_{ij}\}$the rules of linear elasticity

$$\varepsilon_{ik} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_k} + \frac{\partial u_k}{\partial x_i}\right); \qquad (4a,b,c)$$

$$\varepsilon_{ik}(\sigma) = \frac{1+\nu}{E}\left(\sigma_{ik} - \frac{\nu}{1+\nu}\,\sigma_a\delta_{ik}\right); \qquad \frac{\partial \sigma_{ij}}{\partial x_i} = -f_j$$

where $\delta_{ij} = 1$ if $i = j$; $\delta_{ij} = 0$ if $i \neq j$, and $\sigma_a = \sigma_x + \sigma_y + \sigma_z$. To these conditions must be added the equilibrium condition on the external surface

$$p_i(x,s) = \sigma_{ij}\cos(n,j) \qquad (5)$$

At the joint A_ν between segments $(\nu-1)$ and (ν) there occurs a discontinuity $[\mathbf{u}(x_\nu,y,z)]$ of the displacements across A_ν that defines the gap vector γ (Fig. 1a)

$$[\mathbf{u}(x_\nu,y,z)] = \mathbf{u}_\nu(x_\nu,y,z) - \mathbf{u}_{\nu-1}(x_\nu,y,z) = \gamma_{\nu,\nu-1}(y,z) \qquad (6)$$

where $\gamma = \gamma_x\,\mathbf{i} + \gamma_y\,\mathbf{j} + \gamma_z\,\mathbf{k}$. Here γ_x defines the dilatation of the gap. This is subjected to the impenetrability condition

$$\gamma_x(y,z) \geq 0 \qquad (8)$$

if in the initial unloaded state $\gamma = 0$. γ_y and γ_z represent contact sliding in directions y and z, respectively.

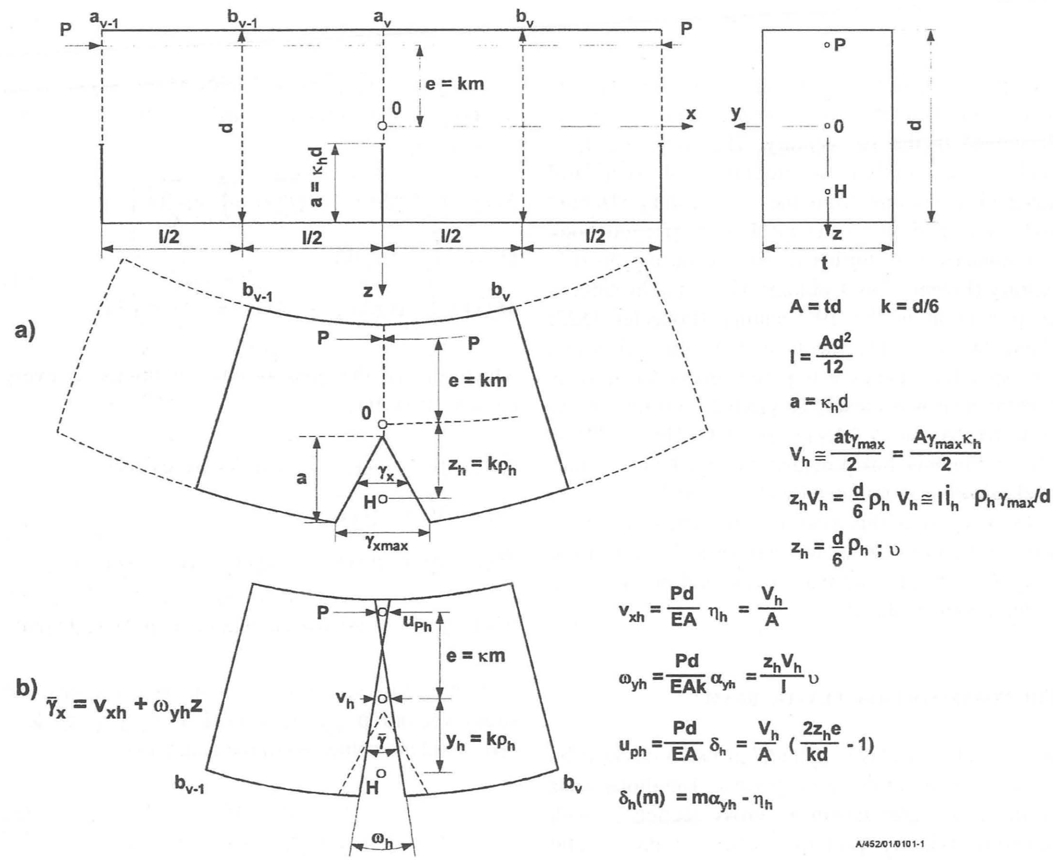


Figure 1
Deformation at dry joint of segmental beam.
a) Actual state of deformation.
b) Linearized state of deformation

If $\{u', \varepsilon', \gamma'\}$ is a possible kinematic state of the cracked beam induced by load p^* and $\{p''_e, \sigma''_e\}$ is a solution to a loading p''_e of the uncracked beam there applies, because of (4a,b,c) and Green's theorem, the equation of virtual stresses :

$$\int_{\Gamma_e} \mathbf{p}'' \cdot \mathbf{u}' \mathrm{d}\Gamma = \int_V \sigma''_{ij}\varepsilon'_{ij}\mathrm{d}V + \sum \int_{\Gamma_e} \mathbf{p}'' \cdot \gamma' \mathrm{d}A \tag{9}$$

The work of virtual load p'' on the displacements u' of the uncracked solution of the beam equals the sum the work of the virtual stresses σ'' on the strains ε' and the corresponding work of virtual stresses p'' on gap deformation γ' induced by load p^*.

In order to extract out of the displacement field $\{u\}$ the effect of the discontinuities caused by the cracks and joints we subject the cracked beam at the endfaces $A(-L/2)$, $A(+L/2)$ to unit force couples N', M''_y, M'''_z, $\{M''''_y, Q''''_z\}$, $\{M'''''_z, Q'''''_y\}$. These induce in the uncracked beam the elastic stress fields according to (9) with $G = E/(2(1+\nu))$

$$\begin{aligned}
&N' = 1 \quad \text{induces} \quad \sigma'_x = \frac{1}{A}; \quad \varepsilon'_x = \frac{1}{EA}; \quad \varepsilon'_y = \frac{-\nu}{EA}; \quad \varepsilon'_z = \frac{-\nu}{EA}\\
&M''_y = 1 \quad \text{induces} \quad \sigma''_x = \frac{z}{I_y}; \quad \varepsilon''_x = \frac{z}{EI_y}; \quad \varepsilon''_y = \frac{-\nu z}{EI_y}; \quad \varepsilon''_z = \frac{-\nu z}{EI_y}\\
&M'''_z = 1 \quad \text{induces} \quad \sigma'''_x = \frac{-y}{A}; \quad \varepsilon'''_x = \frac{-y}{EA}; \quad \varepsilon'''_y = \frac{\nu y}{EA}; \quad \varepsilon'''_z = \frac{\nu y}{EA}
\end{aligned} \tag{10a}$$

$$\begin{aligned}
&\left\{\begin{matrix} Q''''_z = 1 \\ M''''_y = Q''''_z L/2 \end{matrix}\right\} \text{induces} \left\{\begin{matrix} \tau''''_{xz} = \dfrac{S_y(z)}{b_y I_y}; \quad \tau''''_{xy} = \dfrac{2y}{b_y}\dfrac{\partial b_y}{\partial y}\tau''''_{xz}; \quad \gamma''''_{xz} = \dfrac{\tau''''_{xz}}{G}; \quad \gamma''''_{xy} = \dfrac{\tau''''_{xy}}{G} \\ \sigma''''_x = \dfrac{xz}{I_y}; \quad \varepsilon''''_x = \dfrac{xz}{EI_y}; \quad \varepsilon''''_y = \dfrac{-\nu xz}{EI_y}; \quad \varepsilon''''_z = \dfrac{-\nu xz}{EI_y} \end{matrix}\right\}\\
&\left\{\begin{matrix} Q'''''_y = 1 \\ M'''''_z = -Q'''''_y L/2 \end{matrix}\right\} \text{induces} \left\{\begin{matrix} \tau'''''_{xy} = \dfrac{S_z(y)}{b_z I_z}; \quad \tau'''''_{xz} = \dfrac{2z}{b_z}\dfrac{\partial b_z}{\partial z}\tau'''''_{xy}; \quad \gamma'''''_{xy} = \dfrac{\tau'''''_{xy}}{G}; \quad \gamma'''''_{xz} = \dfrac{\tau'''''_{xz}}{G} \\ \sigma'''''_x = \dfrac{-yz}{I_z}; \quad \varepsilon'''''_x = \dfrac{-yx}{EI_z}; \quad \varepsilon'''''_y = \dfrac{\nu xz}{EI_z}; \quad \varepsilon'''''_z = \dfrac{\nu xz}{EI_z} \end{matrix}\right\}
\end{aligned} \tag{10b}$$

These forces correspond to a loading by forces N', M''_y, M'''_z, Q''''_z, Q'''''_y acting at $x = 0$ on lever arms connected to the endfaces $A(-L/2)$ and $A(L/2)$. The work performed by the unit forces N', M''_y, M'''_z at $x = 0$ on the displacements $\{u\}$ at $A(-L/2)$ and $A(L/2)$ induced by the load p^* is according to (9) and (10)

$$\begin{Bmatrix} 1\cdot v_x \\ 1\cdot \omega_y \\ 1\cdot \omega_z \end{Bmatrix} = \begin{Bmatrix} \int \frac{1}{A}\left(u_x(L/2 - u_x(-L/2)\right)\mathrm{d}A \\ \int \frac{z}{I_y}\left(u_x(L/2 - u_x(-L/2)\right)\mathrm{d}A \\ -\int \frac{y}{I_z}\left(u_x(L/2 - u_x(-L/2)\right)\mathrm{d}A \end{Bmatrix} = \begin{Bmatrix} \int_V \sigma'_x\varepsilon_x\mathrm{d}V \\ \int_V \sigma''_x\varepsilon_x\mathrm{d}V \\ \int_V \sigma'''_x\varepsilon_x\mathrm{d}V \end{Bmatrix} + \sum \begin{Bmatrix} \int_A \sigma'_x\gamma_x\mathrm{d}A \\ \int_A \sigma''_x\gamma_x\mathrm{d}A \\ \int_A \sigma'''_x\gamma_x\mathrm{d}A \end{Bmatrix} = \tag{11}$$

$$= \int_V \begin{Bmatrix} 1/A \\ z/I_y \\ -y/I_z \end{Bmatrix} \varepsilon_x \mathrm{d}V + \sum_v \begin{Bmatrix} \left(\frac{1}{A}\int_A \gamma_x \mathrm{d}A\right)_v \\ \left(\frac{1}{I_y}\int_A z\gamma_x \mathrm{d}A\right)_v \\ \left(\frac{-1}{I_z}\int_A y\gamma_x \mathrm{d}A\right)_v \end{Bmatrix} \tag{11}$$

where in the first integral $\varepsilon_x = \left(\sigma_x - \nu\,(\sigma_y + \sigma_z)\right)/E$. Introducing this value into the volume integral we obtain

$$\int_V \begin{Bmatrix} 1/A \\ z/I_y \\ -y/I_z \end{Bmatrix} \varepsilon_x \mathrm{d}V + \int_{-L/2}^{L/2} \begin{Bmatrix} \left(\frac{1}{EA}\int_A \sigma_x \mathrm{d}A - \nu\int_A (\sigma_y + \sigma_z)\mathrm{d}A\right) \\ \left(\frac{1}{EI_y}\int_A z\sigma_x \mathrm{d}A - \nu\int_A z(\sigma_y + \sigma_z)\mathrm{d}A\right) \\ \left(\frac{-1}{EI_z}\int_A y\sigma_x \mathrm{d}A - \nu\int_A y(\sigma_y + \sigma_z)\mathrm{d}A\right) \end{Bmatrix} \mathrm{d}x \tag{12}$$

According to (1) the first surface integrals within the brackets can be expressed as line integrals of N, M_y, M_z, respectively. Because $\nu < 0.2$ and $|\sigma_y + \sigma_z| < |\sigma_x|$, the second surface integrals can be neglected. Observing further that the integrals of the second terms of (11) can be expressed by the gap volumes V_{hv} of the gaps at A_v and their centroid coordinates y_{hv}, z_{hv}

$$\int_{A_v} \gamma_x \mathrm{d}A = V_{hv}\ ; \quad \int_{A_v} y\gamma_x \mathrm{d}A = y_{hv}V_{hv}\ ; \quad \int_{A_v} z\gamma_x \mathrm{d}A = z_{hv}V_{hv} \tag{13}$$

the equation (11) can be written

$$v_x = \int_{-L/2}^{L/2} \frac{N}{EA}\,\mathrm{d}x + \sum_v \frac{V_{hv}}{A_v} \tag{14a}$$

$$\omega_y = \int_{-L/2}^{L/2} \frac{M_y}{EI_y}\,\mathrm{d}x + \sum_v \frac{z_{hv}V_{hv}}{I_{yv}} \tag{14b}$$

$$\omega_z = \int_{-L/2}^{L/2} \frac{M_z}{EI_z}\,\mathrm{d}x - \sum_v \frac{y_{hv}V_{hv}}{I_{zv}} \tag{14c}$$

Applying the unit forces Q_y'''', Q_z'''' we obtain the shear deformations v_y and v_z of the beam

$$v_y = \int_{-L/2}^{L/2} \left(\frac{-M_z x}{EI_z} + \frac{Q_y}{GA}\,\xi_y\right)\mathrm{d}x + \sum_v \left(\frac{-x_v y_{hv} V_{hv}}{I_z} + \overline{\gamma}_y\right)_v \tag{14d}$$

$$v_z = \int_{-L/2}^{L/2} \left(\frac{M_y x}{EI_y} + \frac{Q_z}{GA}\,\xi_z\right)\mathrm{d}x + \sum_v \left(\frac{x_v z_{hv} V_{hv}}{I_y} + \overline{\gamma}_z\right)_v \tag{14e}$$

where

$$\overline{\gamma}_y = \int \frac{S_z}{I_z}\gamma_y\left(1 + \frac{2z}{b_z}\frac{\partial b_z}{\partial y}\right)\mathrm{d}y\,; \quad \overline{\gamma}_z = \int \frac{S_y}{I_y}\gamma_z\left(1 + \frac{2y}{b_y}\frac{\partial b_y}{\partial z}\right)\mathrm{d}z$$

The integrals represent the deformations v_e, ω_e of the elastic uncracked beam whereas the sums represent the discontinuities of the displacement field of an assemblage of rigid bodies

elastic monolithic beam	assemblage of rigid bodies	
$v_{ye} = \int_L \frac{N}{EA}\,\mathrm{d}x$	$v_{yh} = \sum_v \left(\frac{V_h}{A}\right)_v \geq 0$	(15a, b)
$\omega_{ye} = \int_L \frac{M_y}{EI_y}\,\mathrm{d}x$	$\omega_{yh} = \sum_v \left(\frac{z_h V_h}{I_y}\right)_v$	(16a, b)
$\omega_{ze} = \int_L \frac{M_z}{EI_z}\,\mathrm{d}x$	$\omega_{zh} = -\sum_v \left(\frac{y_h V_h}{I_z}\right)_v$	(17a, b)
$v_{ye} = \int_L \left(\frac{-M_z x}{EI_z} + \frac{Q_y \xi_y}{GA}\right)\mathrm{d}x$	$v_{yh} = \sum_v \left(\frac{-x y_h V_h}{I_z} + \overline{\gamma}_y\right)_v$	(18a, b)
$v_{ze} = \int_L \left(\frac{M_y x}{EI_y} + \frac{Q_z \xi_z}{GA}\right)\mathrm{d}x$	$v_{zh} = \sum_v \left(\frac{x z_h V_h}{I_y} + \overline{\gamma}_z\right)_v$	(19a, b)

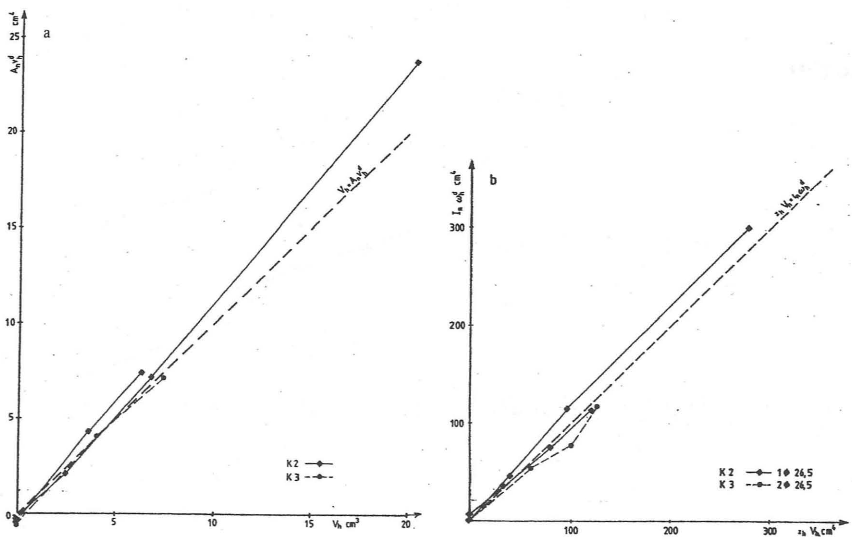


Figure 2
Test of prestressed granite beam with unbonded tendons, net area of section A_n.
a) Measured extension v_h^d of centroid axis versus gap volume V_h.
b) Measured mutual rotation ω_h^d versus gap moment $z_h V_h$

The equations (14) together with the equations (15–19) express that the generalized mutual longitudinal displacements $\Delta u_x(x,y)$ of the endfaces of the monolithic beam Δu_{xe} as well as those of the corresponding rigid body assemblage Δu_{xh} are linear functions of the cross sectional coordinates (Fig. 1b):

$$\Delta u_{xe} = v_{xe} + \omega_{ye} z - \omega_{ze} y\,; \qquad \Delta u_{ye} = \text{constant}\,; \qquad \Delta u_{ze} = \text{constant} \tag{20a}$$

$$\Delta u_{xh} = v_{xh} + \omega_{yh} z - \omega_{zh} y\,; \qquad \Delta u_{yh} = \text{constant}\,; \qquad \Delta u_{zh} = \text{constant} \tag{20b}$$

Because the separating surface constitutes a dry joint, the normal stress σ_x and the resulting shear stress $\tau_x = \tau_{xy}\mathbf{j} + \tau_{xz}\mathbf{k}$ are assumed to follow Coulomb's friction law

$$\sigma_x(y,z) \leq 0\,; \qquad |\tau_x| \leq |\sigma_x| \tan\varphi \tag{21}$$

where φ represents the angle of friction at the joint.

Provided the structure in the unloaded state is stress- and gap-free (σ^o, $\gamma^o = 0$) and the loading is proportional (i.e. p* increases without reversals) then there holds : if load p* induces $\{\sigma, u, \gamma\}$, load λp^* induces $\{\lambda\sigma, \lambda u, \lambda\gamma\}$ (multiplicity rule).

$$v_{xh} = \int_{A_v} \frac{\gamma\, dA}{A} = \frac{V_h}{A}$$

$$\omega_{yh} = \int_{A_v} \frac{\gamma\, z dA}{I_y} = \frac{z_h V_h}{I_y}$$

$$\omega_{zh} = -\int_{A} \frac{\gamma\, y dA}{I_z} = \frac{y_h V_h}{I_z}$$

$$v_{hy} = \int_{A_v} (\gamma_y \tau^4{}_y + \gamma_z \tau^4{}_z)\, dA$$

$$v_{hz} = \int_{A_v} (\gamma_y \tau^5{}_y + \gamma_z \tau^5{}_z)\, dA$$

$$\omega_{hx} = \int_{A_v} (\gamma_y \tau^6{}_y + \gamma_z \tau^6{}_z)\, dA$$

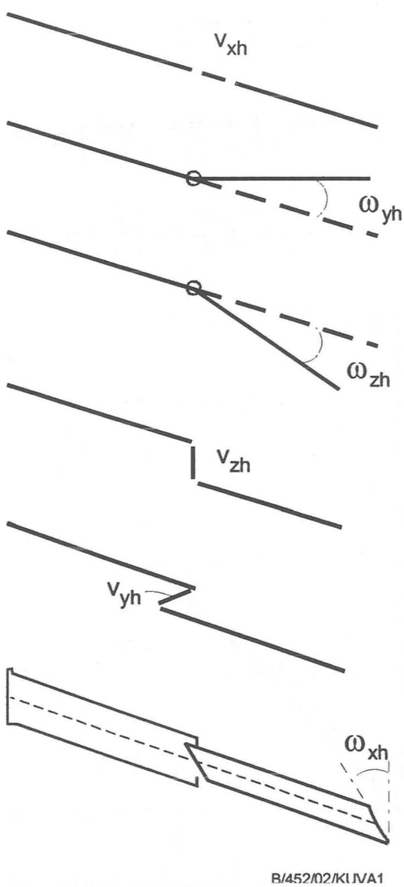


Figure 3
Discontinuities of the displacements of the beam axis

We consider an assemblage (Fig. 1b) of two equal half segments (v–1) and (v) of the beam separated by a joint (v) that represents a plane of symmetry of the assemblage. The assemblage is at its middle section (a) loaded by an axial compressive force P with eccentricities $y_p = -k_y m_y$, $z_p = -k_z m_z$ and shear forces Q_y and Q_z only. Here k_y, k_z are the core point distances and m_y, m_z denote the relative eccentricities of P, respectively. The symmetric load P induces then in the assemblage a symmetric field of stress and strain $\{\sigma^s,\varepsilon^s\}$ to which, according to (15–19), correspond the symmetric generalized deformations v_i^s, ω_i^s. Analogously Q_z , with constant P and $Q_y = 0$, induces only v_z, which implies that the multiplicity rule applies to P and Q_z separately. Hence

With constant Q:

In the uncut segment	In the joint (v)	
$v_{xe} = -\dfrac{Pl}{EA}$	$v^v_{xh} = \dfrac{P^v d}{EA}\,\eta_h(m_y,m_z)^v = \dfrac{V^v_h}{A}$	(22a,b)
$\omega_{ye} = \dfrac{M_y l}{EI_y}$	$\omega^v_{yh} = \dfrac{P_v d}{EA\bar{k}_z}\,\alpha_{yh}(m_y,m_z)^v = \dfrac{z^v_h V^v_h}{I_y}$	(23a,b)
$\omega_{ze} = \dfrac{M_z l}{EI_z}$	$\omega^v_{zh} = \dfrac{-P^v d}{EA\bar{k}_y}\,\alpha_{zh}(m_y,m_z)^v = \dfrac{y^v_h V^v_h}{I_z}$	(24a,b)

whereas v_{ye}, v_{ze}, v_{yh}, v_{zh} remain unchanged because of symmetry of loading.

Equations (17b–18b) determine the linearized gap deformation (Fig. 1b)

$$\bar{\gamma}_x(y,z) = v_{xh} + \omega_{yh} z - \omega_{zh} y = \frac{Pd}{EA}\left(\eta_h + \alpha_{yh}\frac{z}{k_z} - \alpha_{zh}\frac{y}{k_y}\right) \tag{25}$$

as function of load P. The parameters η_h, α_h determine the interpenetration u_p at (y_p,z_p) where, because of (25)

$$u_p = \frac{Pd}{EA}\,\delta_h$$

$$\delta_h = \alpha_{yh} m_z - \alpha_{zh} m_y - \eta_h\,; \qquad \frac{\partial \delta_h}{\partial m_y} = 2\alpha_{zh}; \tag{26}$$

$$\frac{\partial \delta_h}{\partial m_z} = 2\alpha_{yh}$$

$$\eta_h = \frac{1}{2}\left(\frac{\partial \delta_h}{\partial m_z} - \frac{\partial \delta_h}{\partial m_y}\right) - \delta_h$$

The crack volume V_h and the coordinates y_h, z_h of its centroid are, accordingly

$$\begin{aligned} V_h &= Pd\eta_h/E \\ y_h &= \bar{k}_y \rho_{yh} = \frac{i_z^2}{\bar{k}_y}\,\frac{\alpha_{zh}}{\eta_h} \\ z_h &= \bar{k}_z \rho_{zh} = \frac{i_y^2}{\bar{k}_z}\,\frac{\alpha_{yh}}{\eta_h} \end{aligned} \tag{27}$$

If we subsequently apply to the middle section a shearforce Q_z, this will induce an antisymmetric deformation with v_{ze}, v_{zh} proportional to Q_z without effecting v_x, ω_y, ω_z (Kalker 1990). Therefore there applies to v_{ye}, v_{ze} and v_{yh}, v_{zh} at given P, m_y and m_z

$$v^v_{ye} = \frac{Q_y 1}{GA}\,\kappa_y\,; \quad v^v_{yh} = \frac{Q_y 1}{GA}\,\psi_y\,(m_y,m_z) = \bar{\gamma}^v_y \tag{28a,b}$$

$$v^v_{ze} = \frac{Q_z 1}{GA}\,\kappa_z\,; \quad v^v_{zh} = \frac{Q_z 1}{GA}\,\psi_z\,(m_y,m_z) = \bar{\gamma}^v_z \tag{29a,b}$$

Inserting these values $v^v_{xh}, \ldots, v^v_{zh}$ into equations (15b) – (19b) we obtain

$$\begin{aligned} v_{xh} &= \sum\nolimits_v v^v_{xh} = \sum\nolimits_v \left(\frac{|N|\,d}{EA}\,\eta_h(m_y,m_z)\right)_v \\ \omega_{yh} &= \sum\nolimits_v \omega^v_{yh} = \sum\nolimits_v \left(\frac{|N|\,d}{EAk_z}\,\alpha_{yh}(m_y,m_z)\right)_v \\ \omega_{zh} &= \sum\nolimits_v \omega^v_{zh} = \sum\nolimits_v \left(\frac{|N|\,d}{EAk_z}\,\alpha_{zh}(m_y,m_z)\right)_v \end{aligned} \tag{30a}$$

$$\begin{aligned} v_{yh} &= \sum\nolimits_v \left(\frac{x\,|N|\,d}{EAk_y}\,\alpha_{zh}(m_y,m_z) + \frac{Q_y d}{EA}\,\psi_y(m_y,m_z)\right)_v \\ v_{zh} &= \sum\nolimits_v \left(\frac{x\,|N|\,d}{EAk_z}\,\alpha_{yh}(m_y,m_z) + \frac{Q_z d}{EA}\,\psi_z(m_y,m_z)\right)_v \end{aligned} \tag{30b}$$

where v^v_{xh}, ω^v_{yh}, ω^v_{zh} at given m_y, m_z are proportional to N^v at any loading and v^v_{yh}, v^v_{zh} at given m_y, m_z are proportional to N^v only at proportionally increasing Q_y, Q_z.

The equilibrium of segmental beams are determined by 5 redundants, the horizontal thrust X,

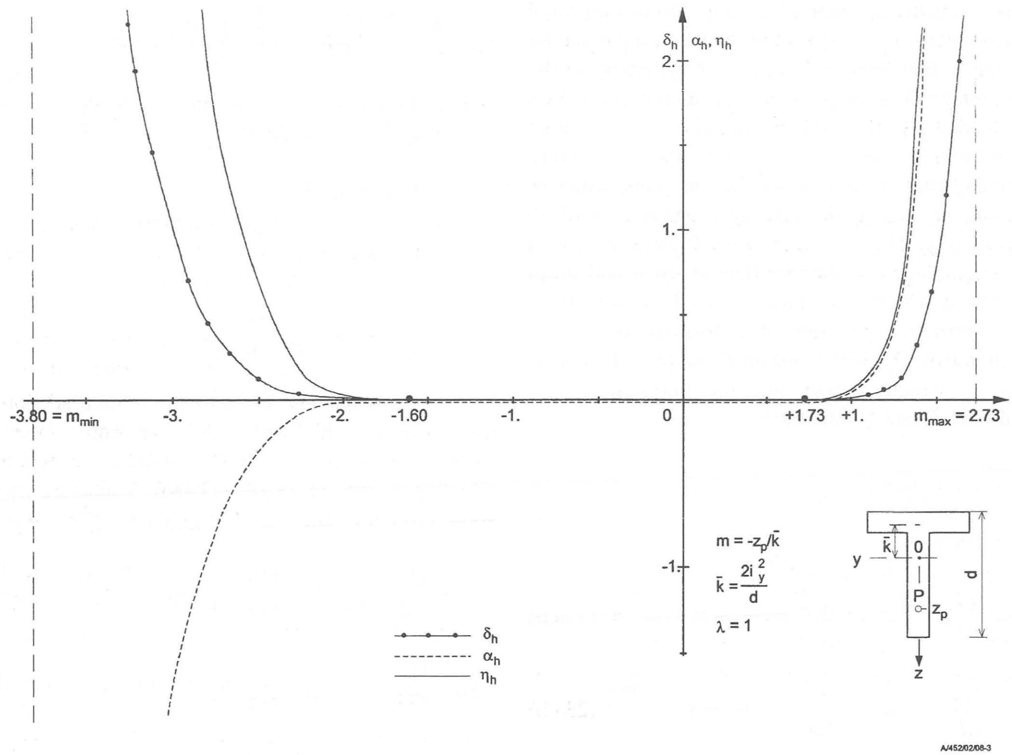


Figure 4
Deformation parameters η_h, α_h, δ_h of segment with T-profile.

the bending moments Y and Z and the shear forces T_y, T_z which act as opposite couples on the ends of rigid lever arms fixed to the end faces $A(L/2)$, $A(-L/2)$. The normal force $N(x)$, the bending moments $M_y(x)$, $M_z(x)$ and the shear forces $Q_y(x)$, $Q_z(x)$ are thus

$$N(x) = N^0(x) - X$$

$$M_y(x) = M_y^0(x) - T_z x - Y$$

$$M_z(x) = M_z^0(x) - T_y x - Z \tag{31}$$

$$Q_y(x) = Q_y^0(x) - T_y$$

$$Q_z(x) = Q_z^0(x) - T_z$$

Inserting these values into (14) and (22–24, 28, 29) we obtain the equations for the determination of redundant quantities X, Y, Z, T_y, T_z

$$X\int \frac{\mathrm{d}x}{EA} = \int_L \left(\frac{N^0}{EA}\right)\mathrm{d}x - v_x + \sum\nolimits_v \left(\frac{|N|\,d}{EA}\,\eta_h(m_y,m_z)\right)_v$$

$$Y\int \frac{\mathrm{d}x}{EI_y} = \int_L \left(\frac{N_y^0}{EI_y}\right)\mathrm{d}x - \omega_x + \sum\nolimits_v \left(\frac{|N|\,d}{EAk}\,\alpha_{yh}(m_y,m_z)\right)_v \tag{32a}$$

$$Z\int \frac{\mathrm{d}x}{EI_z} = \int_L \left(\frac{N_z^0}{EI_z}\right)\mathrm{d}x - \omega_z + \sum\nolimits_v \left(\frac{|N|\,d}{EAk}\,\alpha_{zh}(m_y,m_z)\right)_v$$

$$T_y \int \left(\frac{x^2}{EI_z} + \frac{\xi_y}{GA}\right) dx = \int_L \left(\frac{M_z^0 x}{EI_z} + \frac{Q_y^0 d}{GA}\xi_y\right) dx + \sum_v \left(\frac{x\,|N|\,d}{EAk_y}\alpha_{zh}(m_y,m_z) + \frac{Q_y^0 d}{GA}\psi_y(m_y,m_z)\right)_v$$
$$T_z \int \left(\frac{x^2}{EI_y} + \frac{\xi_z}{GA}\right) dx = \int_L \left(\frac{M_y^0 x}{EI_y} + \frac{Q_z^0 d}{GA}\xi_z\right) dx + \sum_v \left(\frac{x\,|N|\,d}{EAk_z}\alpha_{yh}(m_y,m_z) + \frac{Q_z^0 d}{GA}\psi_z(m_y,m_z)\right)_v \quad (32b)$$

Every integral on the right hand side expresses the share of the monolithic structure whereas the corresponding sum expresses the share of the cracks in the redundants in question.

THE DEFORMATION PARAMETERS OF THE JOINTS AND THEIR APPROXIMATIONS

Closed expressions for the parameters $\eta_h, \ldots, \delta_h$ cannot generally be obtained. Their dependence on the slenderness $\lambda = l/d$ of the segments is rather complicated with one exception where the compressive stress distribution in the cross section is bilinear. This materializes in a beam with very dense crack spacing $\lambda \to 0$ in accordance with the classical theory of bending of reinforced concrete beams. In this exceptional case the contact problem may be solved by elementary means because the parameters $\alpha_{ho}, \eta_{ho}, \delta_{ho}$ are proportional to the slenderness of the segments

$$\dot{\alpha}_{yho} = \lambda\dot{\alpha}_{yh}(m_y,m_z)\,; \qquad \alpha_{zho} = \lambda\dot{\alpha}_{zh}(m_y,m_z)$$
$$\eta_{ho} = \lambda\dot{\eta}_h(m_y,m_z)\,; \qquad \delta_{ho} = \lambda\dot{\delta}_{zh}(m_y,m_z) \quad (33a)$$

For a rectangular section the quantities $\dot{\eta}_h, \ldots, \dot{\delta}_h$ are with $m_y = 0$, $m_z = m = 6z_p/d$

$$\dot{\eta}_h = (|m|-1)^2/(3-|m|)^2$$
$$\dot{\alpha}_h = \mathrm{sign}(m)(4-|m|)(|m|-1)^2/\left(3(3-|m|)^2\right) \quad (33b)$$
$$\dot{\delta}_h = (|m|-1)^3/\left(3(3-|m|)\right)$$

Lower bound solutions for the stiffness of the structure, with upper bounds for δ_h'', are obtained by Castigliano's minimum principle using Kantorovich's stress function expansions for plates. Upper bound solutions, with lower bounds for δ_h', are obtained by FEM and by Ritz method using the minimum principle of the potential energy (Parland, Heinisuo, Koivula 1982).

The dependence of the parameters $\eta_h, \alpha_h, \delta_h$ on λ appear on Figs. 4 and 5. After a linear phase at small λ, according to (33b), there follows a nonlinear phase for intermediate values of λ, and if $\lambda > 1$ the parameters approach asymptotically limit values $\eta_h(m,\infty)$, $\alpha_h(m,\infty)$ and $\delta_h(m,\infty)$. For a segment with rectangular cross section the functions $\eta_h(m,\lambda)$, $\alpha_h(m,\lambda)$ and $\delta_h(m,\lambda)$ have been determined using upper bound and lower bound solutions $\{u',\sigma'\}$, $\{u'',\sigma''\}$, respectively. It appears (Fig. 5) that not only stiffness parameters δ_h are subjected to stiffness rule $\delta_h''(m,\lambda) \geq \delta_h'(m,\lambda)$ but also $\eta_h''(m,\lambda) \geq \eta_h'(m,\lambda)$ and $\alpha_h''(m,\lambda) \geq \alpha_h'(m,\lambda)$.

From the upper and lower bound solutions the following average approximations have been determined for $\lambda \to \infty$

$$\delta_h(m,\infty) \cong a\left(1-(|m|-2)^2\right)^r \dot{\delta}_h$$
$$\eta_h(m,\infty) \cong \left(3 + r(2-|m|)|m|\right)\delta_h(m,\infty)/\left(1-(2-|m|)^2\right) \quad (34a)$$
$$\alpha_h(m,\infty) \cong \left(4-|m| + r(2-|m|)\delta_h(m,\infty)\right)/\left(1-(2-|m|)^2\right)$$
$$\rho_h(\mathrm{m},\bullet) \cong 3\left(4-|m| + r(2-|m|)\right)/\left(3 + r(2-|m|)|m|\right)$$

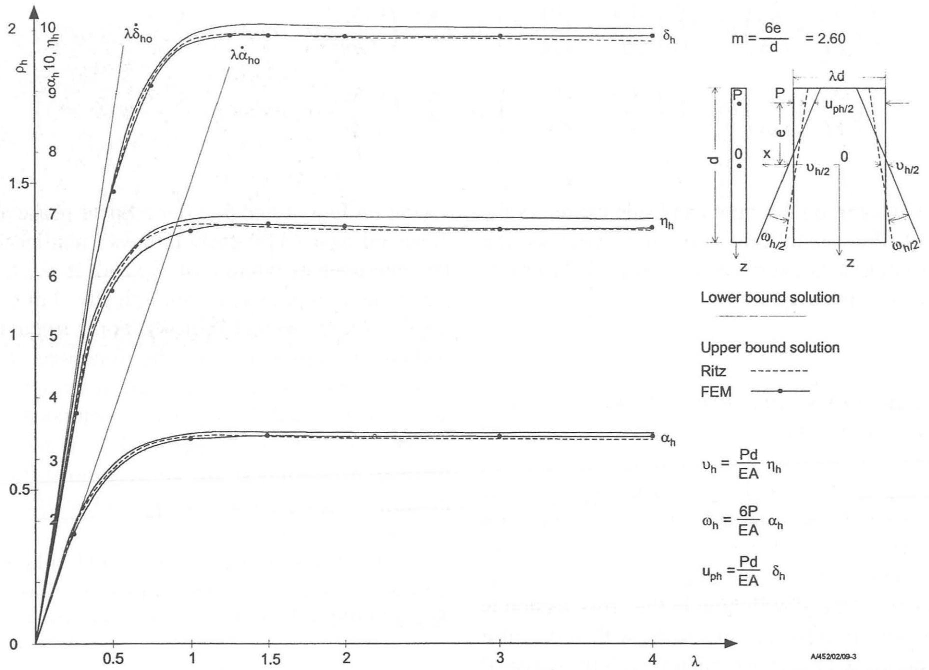
with $a \cong 0.74$ and $r \cong 0.55$.

If the joint can be considered as a plane of symmetry the constant slips γ_y, γ_z are dependent only on the eccentricities m_y, m_z of P, but not on P itself. Instead they depend linearly on Q_y, Q_z at proportional loading. Hence

$$\overline{\gamma}_y \cong \frac{Q_y d}{EA}\,\frac{\psi_y(m_y,\lambda)}{\tan\varphi}; \qquad \overline{\gamma}_z \cong \frac{Q_z d}{EA}\,\frac{\psi_z(m_z,\lambda)}{\tan\varphi} \quad (34b)$$

where $\overline{\psi}(m,\lambda)$ is the value of $\overline{\psi}$ corresponding to $\varphi = \pi/4$.

Because the opening of the cracks may considerably change the mechanical behaviour of the structure an assessment of the volume and the shape of the crack and their dependence on the compressive force is necessary.



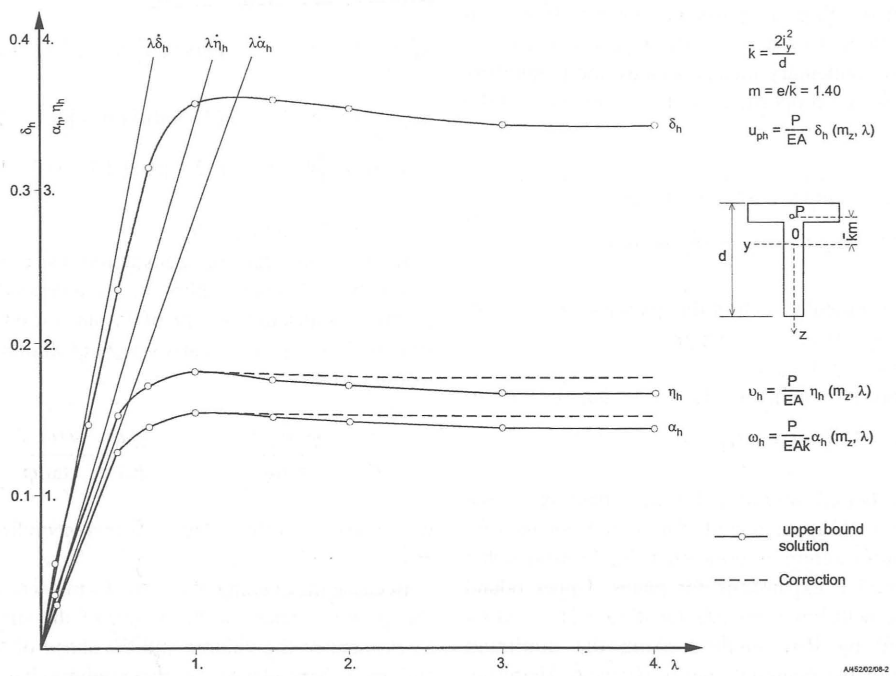


Figure 5
Dilatation parameter η_h, rotation parameter α_h and interpenetration parameter δ_h versus slenderness ratio $\lambda = l/d$.

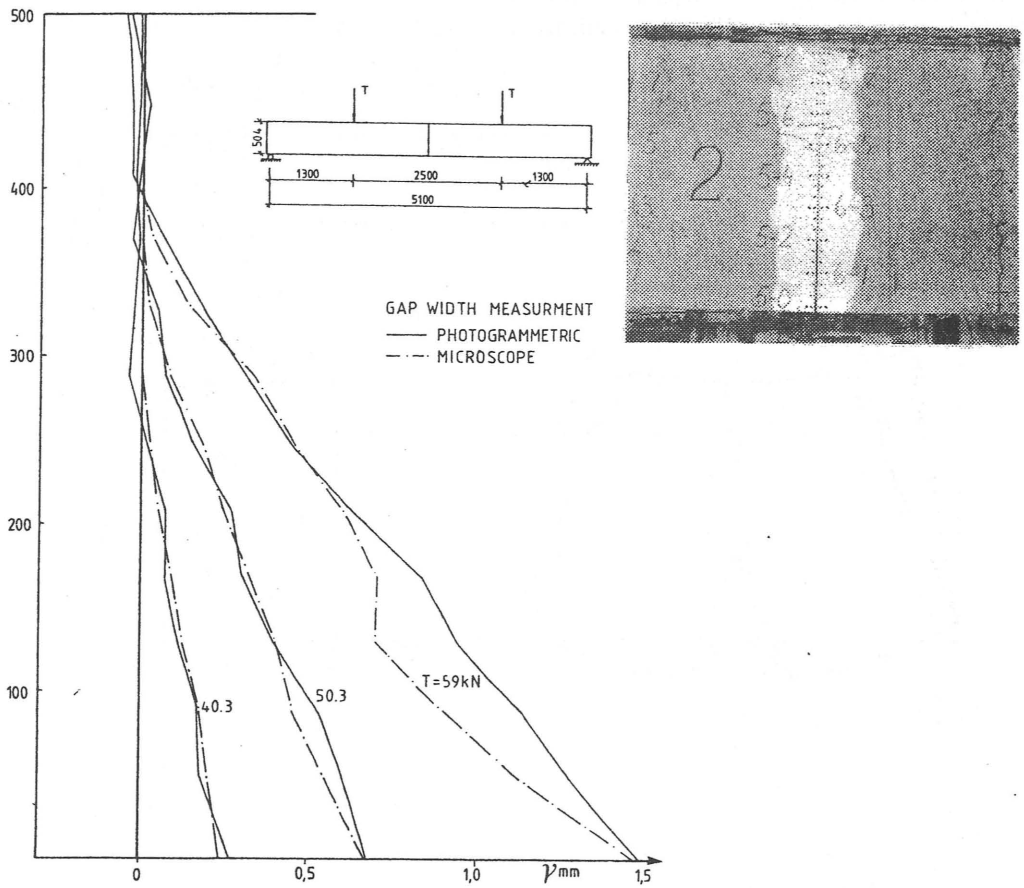


Figure 6
Measured gaps γ of dry joint of prestressed concrete beam with unbonded tendons. Note the linearity of γ in A_+ and zero constancy in A_-

In the limiting case $\lambda \to 0$ corresponding to the classical theory of reinforced concrete the continuous compressive stress distribution $\sigma_x^o(y,z) \leq 0$ is linear in a part A_- of A and zero on the remaining part $A_+ = A - A_-$.

If we consider a symmetrical assemblage of two segment halves $(v-1)$, (v) with length l loaded at $\mathbf{r}_p \subset A_-$ by a compressive normal force $\mathbf{P} = -P\mathbf{i}$, then $\mathbf{P}$ induces a linear stress distribution $\{\sigma_{x-}\} \leq 0$ in $A_- \subset A$ and corresponding strain $\varepsilon_{x-} = \sigma_{x-}/E$. These ε_{x-} define linear deformations $v_{x-} = \varepsilon_{x-} l$ which can be regarded as interpenetrations of the rigid segment halves at the joints. Therefore to every stress block $\{\sigma_{x-}\}$ induced by load $\mathbf{P} = \int_{A-}(\sigma_{x-})\mathrm{d}A\mathbf{i}$ at $\mathbf{r}_p$ there corresponds an interpenetration $\{\gamma_{x-}\} = \{\sigma_{x-}\}1/E$ induced by the fictitious volume $\mathbf{V}_{h-} = \int_{A-}(\gamma_{x-})\mathrm{d}A\mathbf{i} = -(Pl/E)\mathbf{i}$ at $\mathbf{r}_- = \mathbf{r}_p = y_p\mathbf{j} + z_p\mathbf{k}$.

The linear continuation of of $\{\sigma_{x-}\}$ and $\{\gamma_{x-}\}$ into A_+ induces again a linear tensile stress $\{\sigma_{x+}\}$ in A_+ with resultant $\mathbf{H} = \int_{A+}(\sigma_{x+})\mathrm{d}A\mathbf{i}$ at $\mathbf{r}_h = y_h\mathbf{j} + z_h\mathbf{k}$ and a gap deformation $\{\gamma_{x+}\} \geq 0$ with gap volume $V_h = Hl/E$.

As $\sigma_{x-}(A_-) \leq 0$, $\sigma_{x-}(A_+) = 0$ and $\sigma_{x+}(A_+) \geq 0$, $\sigma_{x+}(A_-) = 0$ there holds also $\gamma_{x-}(A_-) \leq 0$, $\gamma_{x-}(A_+) = 0$ and $\gamma_{x+}(A_+) \geq 0$, $\gamma_{x+}(A_-) = 0$. Because furthermore σ_{x+} and γ_{x+} are linear continuations of σ_{x-} and γ_{x-}, respectively, the

sums $(\sigma_{x+}) + (\sigma_{x-})$ and $(\gamma_{x+}) + (\gamma_{x-})$ represent linear distributions σ_{xe} and γ_{xe} induced by the fictitious force-void couple (**P**, **H**):

$$\sigma_{xe} = \frac{N}{A}\left(1 + \frac{z_N z}{i_y^2} + \frac{y_N y}{i_z^2}\right) = \sigma_{x+}(A_+) + \sigma_{x-}(A_-) \tag{35}$$

with $\sigma_{x+}(A_+) = \sigma_{xe}(A_+)$; $\sigma_{x-}(A_-) = \sigma_{xe}(A_-)$

and

$$\gamma_{xe} = \frac{V_e}{A}\left(1 + \frac{z_v z}{i_y^2} + \frac{y_v y}{i_z^2}\right) = \gamma_{x+} + \gamma_{x-} \tag{36}$$

with $\gamma_{x+}(A_+) = \gamma_e(A_+)$; $\gamma_{x-}(A_-) = \gamma_e(A_-)$

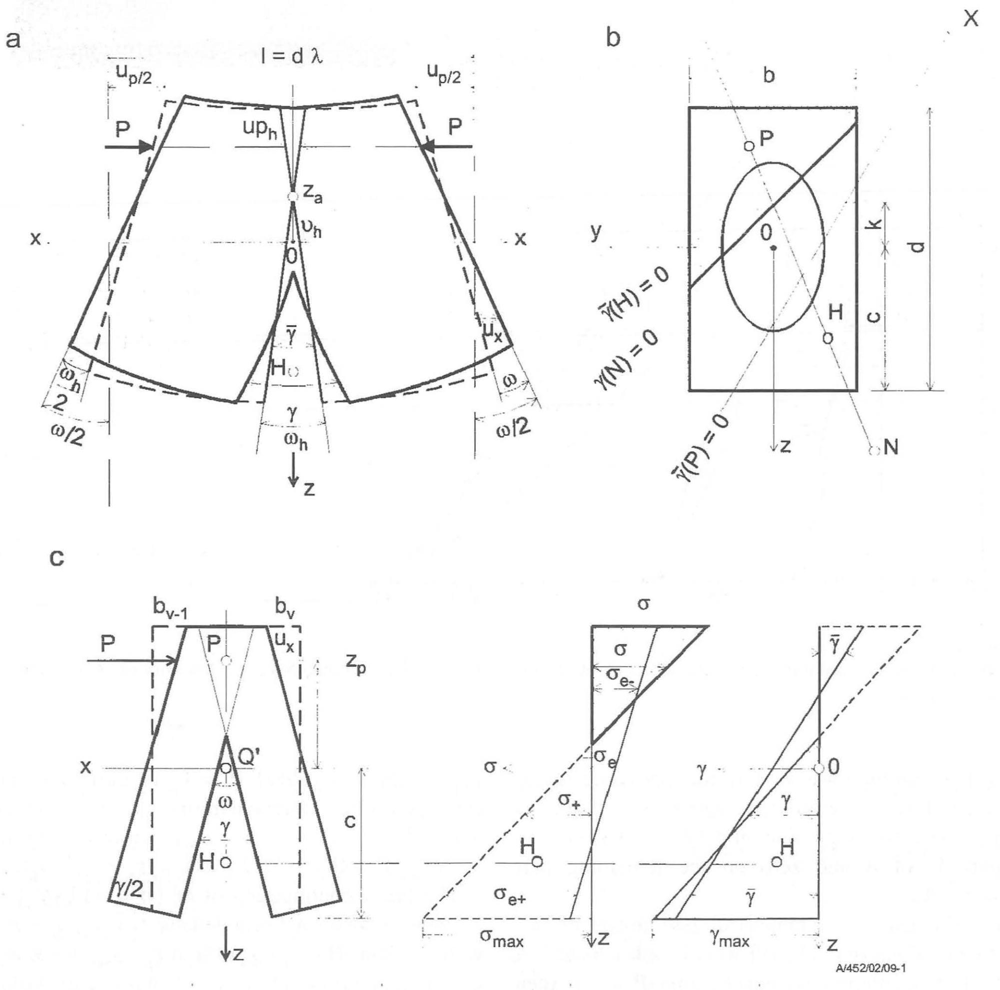


Figure 7

Stresses and gap deformations at dry joint subjected to eccentrical compression P.

a) Actual crack width γ and linearized crack width $\overline{\gamma}$ at finite slenderness $\lambda = l/d$.

b) Neutral lines $L(N) = \gamma = 0$, $L(H) = \overline{\gamma}(H)$, $L(P) = \overline{\gamma}(P) = 0$ induced by N, H and P, respectively, have concurrent point X.

c) Stress and deformations in the case $\lambda = 0$.

Because of the equivalence $\sigma_{xe} = (\sigma_{x+}) + (\sigma_{x-})$ there holds $N = H - P$; $Ny_N = Hy_h - Py_p$; $Nz_N = Hz_h - Pz_p$; $y_h = y_v$; $z_h = z_v$. Hence

$$\sigma_{xe} = \frac{H}{A}\left(1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2}\right) - \frac{P}{A}\left(1 + \frac{z_P z}{i_y^2} + \frac{y_P y}{i_z^2}\right) = \sigma_{xe+} + \sigma_{xe-} \tag{37a}$$

$$\gamma_{xe} = \frac{V_h}{A}\left(1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2}\right) - \frac{V_{h-}}{A}\left(1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2}\right) = \overline{\gamma}_{x+} + \overline{\gamma}_{x-} \tag{37b}$$

Thus the fictitious force-void couple (**P**, **H**) induces linear distributions σ_{xe} and γ_x

$$\sigma_{xe-} = \frac{-P}{A}\left(1 + \frac{z_P z}{i_y^2} + \frac{y_P y}{i_z^2}\right); \qquad \sigma_{xe+} = \frac{H}{A}\left(1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2}\right) \tag{38a}$$

$$\overline{\gamma}_{x-} = \frac{-V_{h-}}{A}\left(1 + \frac{z_P z}{i_y^2} + \frac{y_P y}{i_z^2}\right); \qquad \overline{\gamma}_{x+} = \frac{V_h}{A}\left(1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2}\right) \tag{38b}$$

which are equivalent to the bilinear distributions σ_{x-}, σ_{x+} and γ_{x-}, γ_{x+}, respectively. σ_{xe-} represents the linearized stress σ_{x-} induced by P in the monolithic beam at the joint, whereas $\overline{\gamma}_{x+}$ represents the linearized distribution of the axial discontinuity $[u_x(y,z)]$ induced by P at the joint in question.

The relations between compressive force P, the eccentricities y_p, z_p, the crack volume V_h and its centroid coordinates y_h, z_h attain an involutive form when $\lambda \to 0$. Because of (38a) and $V_h = Hl/E$ there holds

$$H = P\dot{\eta}_h(P)\,; \qquad z_h(P) = \frac{i_y^2}{k_z}\,\frac{\dot{\alpha}_{yh}(P)}{\dot{\eta}_h(P)}\,; \qquad y_h(P) = \frac{i_z^2}{k_y}\,\frac{\dot{\alpha}_{zh}(P)}{\dot{\eta}_h(P)} \tag{39a,b,c}$$

where $\dot{\eta}_h(P)$, $\dot{\alpha}_{yh}(P)$, $\dot{\alpha}_{zh}(P)$ denote the values corresponding to position $\mathbf{r}_p = y_p\mathbf{j} + z_p\mathbf{k}$. Because of reciprocity the force H at $\mathbf{r}_h = y_h\mathbf{j} + z_h\mathbf{k}$ induces force P at $\mathbf{r}_p$

$$P = H\dot{\eta}_h(H)\,; \qquad z_P(H) = \frac{i_y^2}{k_z}\,\frac{\dot{\alpha}_{yh}(H)}{\dot{\eta}_h(H)}\,; \qquad y_P(H) = \frac{i_z^2}{k_y}\,\frac{\dot{\alpha}_{zh}(H)}{\dot{\eta}_h(H)} \tag{40a,b,c}$$

The expressions (39) can be interpreted as a transformation $T = \{T_x, T_{yz}\}$ of triad $S_p = \{P, r_p\}$ into a triad $S_H = \{H, r_h\}$ where $\{r_p\} = \{y_p, z_p\}$ and $\{r_h\} = \{y_h, z_h\}$. Relations (39) and (40) can thus be written

$$T(S_P) = \begin{Bmatrix} T_x(P) \\ T_{yz}(r_P) \end{Bmatrix} = \begin{Bmatrix} H \\ r_h \end{Bmatrix} = S_H \tag{41a}$$

$$T(S_H) = \begin{Bmatrix} T_x(H) \\ T_{yz}(r_h) \end{Bmatrix} = \begin{Bmatrix} H \\ r_h \end{Bmatrix} = S_P \tag{41b}$$

The involution is expressed according to (41) by the relations

$$TTS_H = TS_p = S_H\,; \qquad TTS_p = TS_H = S_p \tag{42}$$

If the principal axes y and z are axes of symmetry a σ_x-distribution induced by a pure moment M_y with $P = -H$ on the z-axis is antisymmetric with internal lever arm $HP = r_h - r_p$. This lever arm is independent of any additional centrical normal force N. For a rectangular cross section $A = bd$ the lever arm is $HP = 2d/3$, or expressed by the relative eccentricities $m_z = -z_p/k$, $\rho_{zh} = z_h/k$ with $k = d/6$ (Fig. 10)

$$|m_z| + |\rho_{zh}| \cong 4 \tag{43}$$

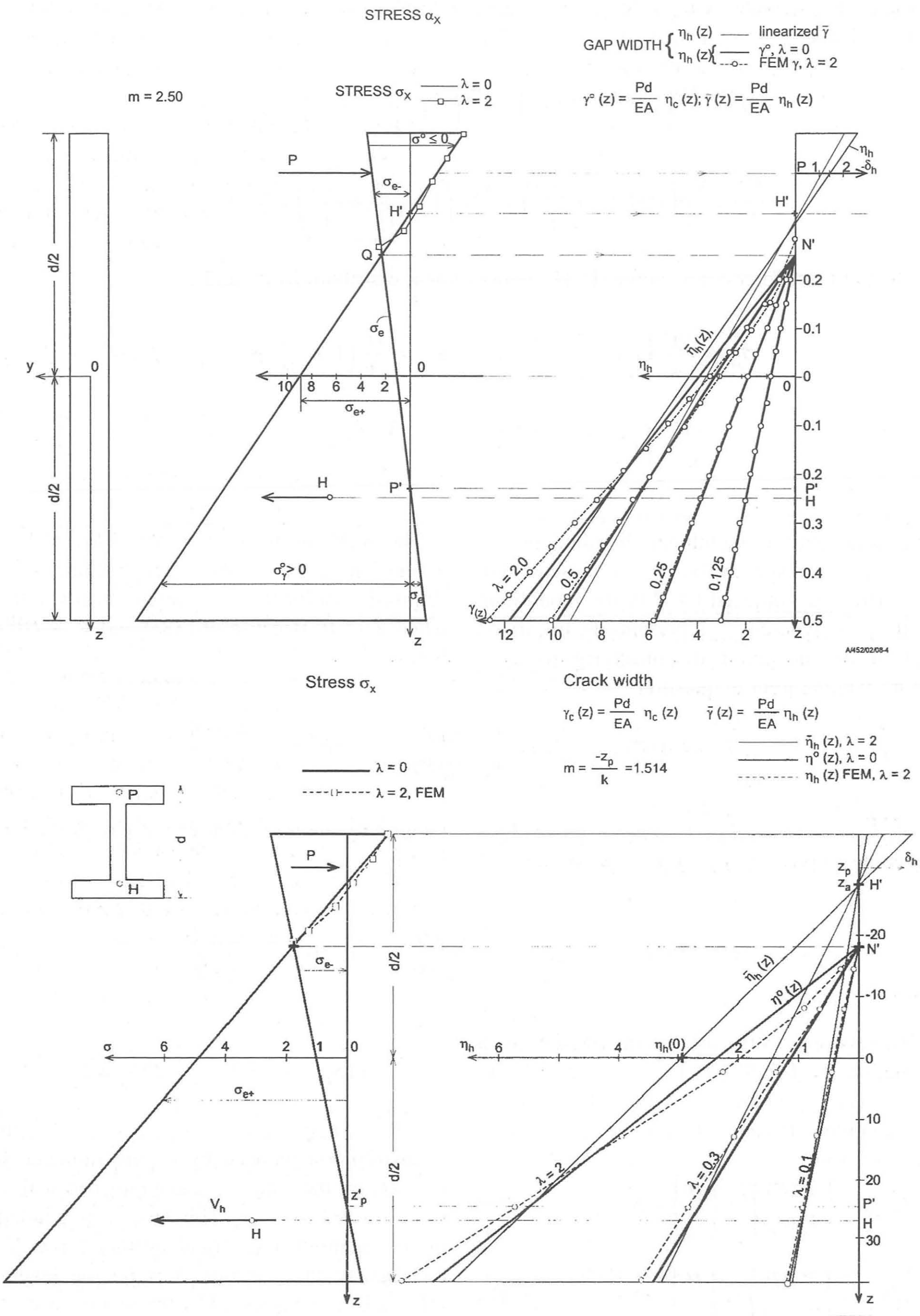


Figure 8
Compressive stress distribution σ_x and gap width $\gamma_x(z)$ of dry joint.
a) Rectangular cross-section. b) I-shaped cross-section

The forces **P**, **H** induce a force $\mathbf{N} = -(\dot{\eta}_h - 1)P\mathbf{i}$ acting at (y_N, z_N) on line PH. The zero lines $L(P)$, $L(H)$, $L(N)$ define mappings, point to line, $N \rightarrow L(N)$; $P \rightarrow L(P)$; $H \rightarrow L(H)$. $L(N)$ determines the axis of local rotation ω^p

$$L(P) = 1 + \frac{z_P z}{i_y^2} + \frac{y_P y}{i_z^2} = 0$$

$$L(N) = 1 + \frac{z_h z}{i_y^2} + \frac{y_h y}{i_z^2} = 0 \tag{44}$$

$$L(N) = 1 + \frac{z_N z}{i_y^2} + \frac{y_N y}{i_z^2} = 0$$

Because of the similarity of the expressions for $\sigma_{xe}(y,z)$ and $\overline{\gamma}_x(y,z)$ we have the following dual relations known from the theory of eccentrically loaded elastic beams:

i) If P (and H) moves along line a^o through the origin O, then the neutral line $L(P)$ (where $\sigma_{xe} = 0$) experiences a translation in the same direction.

ii) If P (and H) moves along a line a outside the origin O, then the neutral line $L(P)$ (and $L(H)$) turns round a fixed point $X(a)$ which is the point of action of **P** whose σ_{xe}-distribution has neutral line $L(P) = a$.

iii) Considering the collinear points P, H and N, the neutral lines $L(P)$, $L(H)$ and $L(N)$ have common point X which is the point of action of **P** or **H** or **N** whose neutral line $L(X)$ is PH. And contrary, if N, P or H are moving along PH the neutral lines $L(N)$, $L(P)$ and $L(H)$, respectively, are turning round X.

Since $V_h = Pd\dot{\eta}_h(P)/E$ we have

iv) If compressive force **P** with centroid at P induces gap volume V_h with centroid at H, then force **P** at H induces gap volume $V_h' = Hd\dot{\eta}_h(H)/E$ at point P (Theorem of reciprocity).

From this follows

v) If **P** moves from a point P' on the conture of the kern ∂K to a point P on the conture ∂A of the convex hull $\overline{A}$ of A, then N moves from $N_{k-} = P'$ through infinity to N_{k+} on ∂K, and $L(N)$ moves from the tangent of ∂A through H' to a tangent point N_{k+} on ∂K. $L(N) = \omega^p$ moves from $L(N_{k-}) = L(P')$ to a tangent $L(N_{k+})$ of ∂A through P.

v′) If **H** moves from point H on ∂A to a point $H_k = N_{k+}$ on ∂K, the axis $\omega_h = L(H)$ moves from a tangent of ∂K through P' to a tangent through P on ∂A.

A numerical comparison shows that the stressblock $\{\sigma_-\}$ for finite λ-values doesn't differ much from the linear one on A_- of the classical theory with $\lambda \rightarrow 0$. Also, the relations between the deformation parameters η_h, α_h, δ_h closely approach the corresponding values for $\lambda \rightarrow 0$ with same m_y, m_z. Hence

$$\alpha_h(\lambda)/\eta_h(\lambda) \cong \dot{\alpha}_{ho}/\dot{\eta}_{ho}\,; \qquad \delta_h(\lambda)/\eta_h(l) \cong \dot{\delta}_{ho}/\dot{\eta}_{ho} \tag{45}$$

This means that the results concerning σ_x obtained for $\lambda \rightarrow 0$ can by induction be extended to values $\lambda \neq 0$. Relations (45) indicate that for given eccentricity of load P the centroid of V_h and the lines $L(P)$, $L(N)$ and $L(H)$ are approximately independent of λ and can be considered as invariants together with their points of intersections P', N' and H' with PH.

For some symmetric profiles the γ_--distribution along the vertical symmetry line $y = 0$ has been calculated. In Fig. 8a the distribution $\gamma(z)$, being affine to $\eta_h(z)$, is determined for different λ-values by using the line through $\eta_h(P) = \delta_h$ and $\eta_h(O)$. The zero-point of $\gamma(z)$ is very close to the theoretical point H'. In Fig. 8b the theoretical point H' is used. The calculated σ_x and γ-diagrams show good agreement with the corresponding linear values of σ_{x+} and γ_c. The difference between calculated γ and smoothed γ^p increases with growing λ, but doesn't exceed 7% when $\lambda = 2$. Also the reciprocity relation between the position vectors $Z(H)$ and $Z(P)$ seems well established as is seen from Fig. 9. If the cross-section has double symmetry the distance $z_h - z_p$ between H and P remains approximately constant (Fig. 10).

The numerical comparisons carried out, confined to symmetric profiles, cover only in part the general theory developed. Nevertheless they show conclusively that in the most important case of symmetrical profiles, with force-void line in the axis of symmetry, the asymptotic approach to the classical theory with $\lambda \rightarrow 0$ provides a satisfactory base for the evaluation of stress and gap width at the joint.

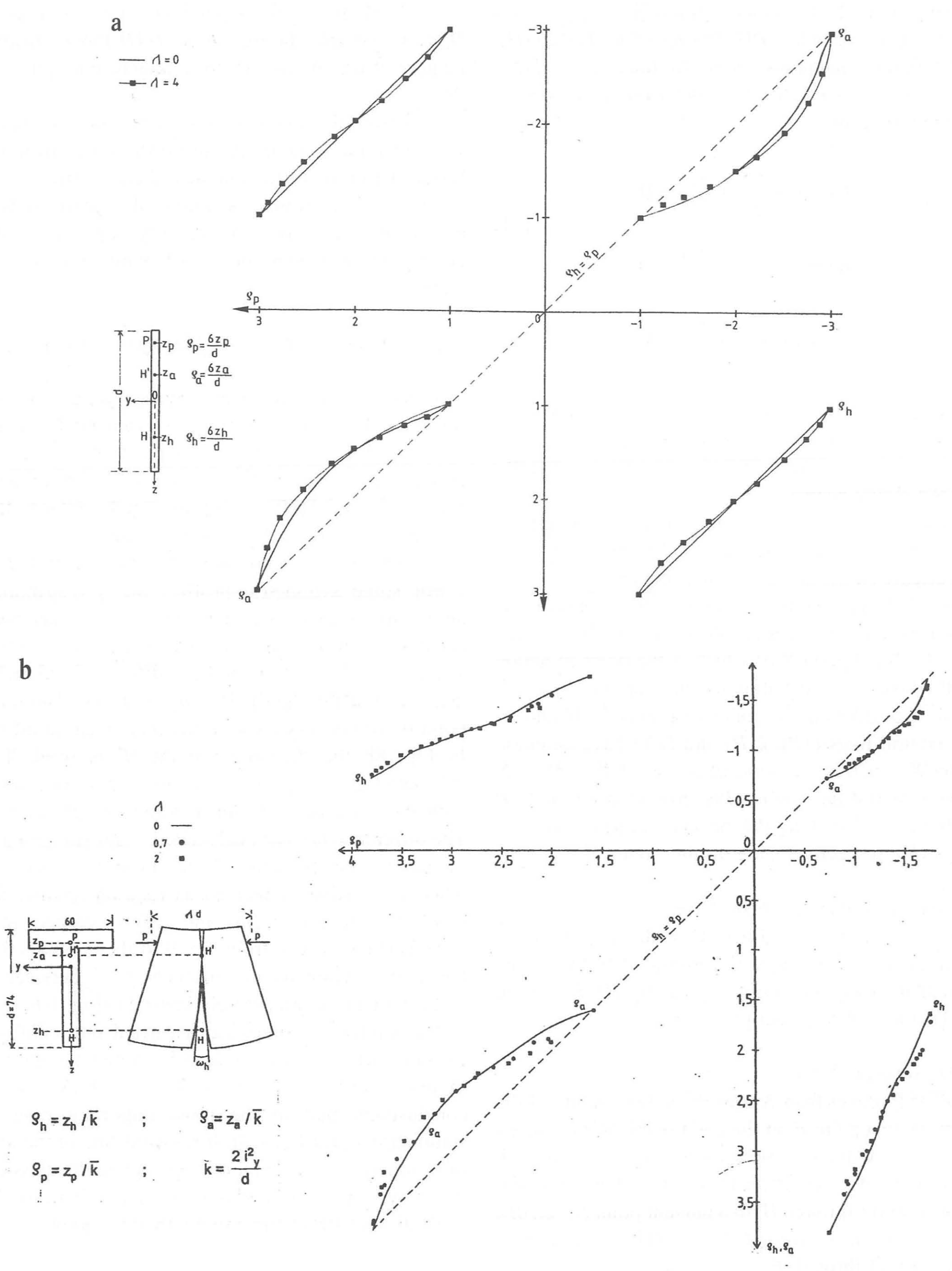


Figure 9. Reciprocity relation of centroid ratios $\rho_h = z_h/\overline{k}$, $\rho_p = z_p/\overline{k}$ and $\rho_a = z_a/\overline{k}$ of gap γ_x of dry joint for various slenderness ratios λ of segment.

a) Rectangular cross-section. b) I-shaped cross-section

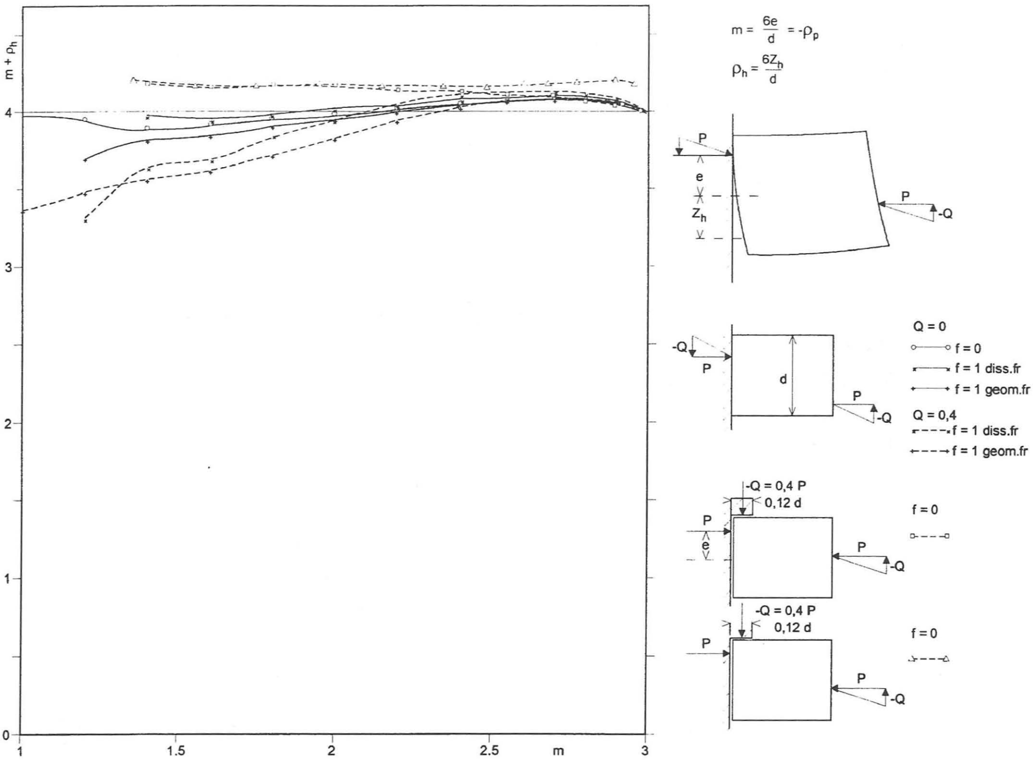


Figure 10
Compression-void lever arm $PH = d(m + \rho_h)/6$ at joint of elastic voussoir to rigid support

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The Roman theatre of Jebleh in Syria: Analysis of the construction form

Teresa Patricio
Tarcis Stevens

Roman architecture plays an important role in terms of variety of structures and variety of materials and means by which they were constructed. The roman theatre of Jebleh in Syria is one of the unknown masterpieces of roman architecture in the Middle East that deserves our attention.

Since 1999 the Syro-Belgian mission carried out analytical investigations at the roman theatre of Jebleh in Syria. The project was started at the behest of Prof. Dr. Jamal Al Ahmar, Director-General of Antiquities and Museums of Syria, in agreement with Mr. Jamal Haidar, Director of the Archaeological Museum of Lattakia, engineer Fatima Ibrahim is the Director of the Archaeological site of the roman theatre. The Belgium team is under the responsibility of Prof. Karel Van Lerberghe, professor in Assyriology at the K.U.Leuven; Belgium.[1] The team is made up by a number of researchers, technicians and students from Syria and from Belgium. Three missions took place to gather data on: archive research, archaeological research and detailed architectural analysis (survey of remains, construction and structural analysis and survey of weathering forms).

The research project aims the study of the building in view of its conservation and its integration in the city of Jebleh. Part of the analysis of the theatre is dealing with a thorough study including all its architectural features. For this paper the analysis of the construction made of massive masonry walls, vaults and arches are explained and particular details of the construction are presented.

General History of the Theatre

Some authors state that the theatre was built by the emperor Justinianus, 527–565 AD (Jacquot 1927), others state that it was built by the emperor Septimus Severus, 193–211 AD. From the architectural details and from the first results of the excavations we are considered that the theatre was probably built during the Severian dynasty, 193–235 AD, probably in the first half of the 3rd century AD. This question deserves more attention and future research. Nevertheless the roman theatre was situated at the centre of a roman settlement, the city of Gabala.

In the years of 1098–1285 the crusaders occupied the city (Jacquot 1927) and in that time the theatre was transformed into a fortification, like the Bosra theatre in south of Syria. Many authors refer to this transformation as G.Rey after is trip in 1859 (1871: 215), and some archaeological evidences prove it as well. Many are the travellers that visited Jebleh, Arabic travellers as Yakut al-hamoi in 1225 and Ibn Battuta in the 14th century, and especially European travellers as H. Maundrell in 1698, R. Pococke (1745: 199), Louis de Clercq (1881: 36) and G.Rey (1871) in 1859, Max Van Berchemand and Edmond Fatio in 1895 (1914: 94–97). From their travels descriptions,

important information was collected about the theatre.

The oldest pictures known from the theatre are from 1859 or 1860 taken by Louis De Clercq during his trip to Orient (De Clercq, 1881: 36). One can see that the *cavea* structure was still complete for the first and second *maenianum* and that all the openings of the main façade of the *cavea* are completely closed. This filling in of the openings is probably what remains of the late fortification built around the theatre. Comparing the photographs and the nowadays situation and referring to literature we can conclude that many destructions happened to the theatre in the span of time 1860–1930. These destructions, half of the *cavea* structure, were probably due to the fact that the theatre has been used as an open quarry to the Jebleh citizens. Besides, in the end of the nineteenth century and during the first half of the twentieth-century, the substructures were used for shops and animal stable and at the same time, houses were built on top of the *cavea* remains (Jacquot, 1927). In 1949 the General Direction of Antiquities and Museums started a full excavation campaign at the roman theatre (Frèzouls, 1952). In 1962–1964 the houses were demolished.

The city of Jebleh is situated in an earthquake area; a few strong earthquakes known: 476, 859 and 1171 AD. At that moment heavy damages were reported in Jebleh. Nevertheless we still have no information about their consequences to the theatre and implications on further transformations and/or deformations. Furthermore, on the outside structure, no apparent deformations by an earthquake are recognisable.

ANALYSIS OF THE EXISTING STRUCTURE

« . . . The architects of the High Empire reworked the old designs with great virtuosity into varied ensembles of fresh power. But, more and more, they turned from them toward complete enclosure of space by curved surfaces. Confident mastery of their materials made them free to throw great vaults over space and swing great curves around it. Experience taught them to conceal structural support in the body of structural fabric . . . » (Brown 1991, 33).

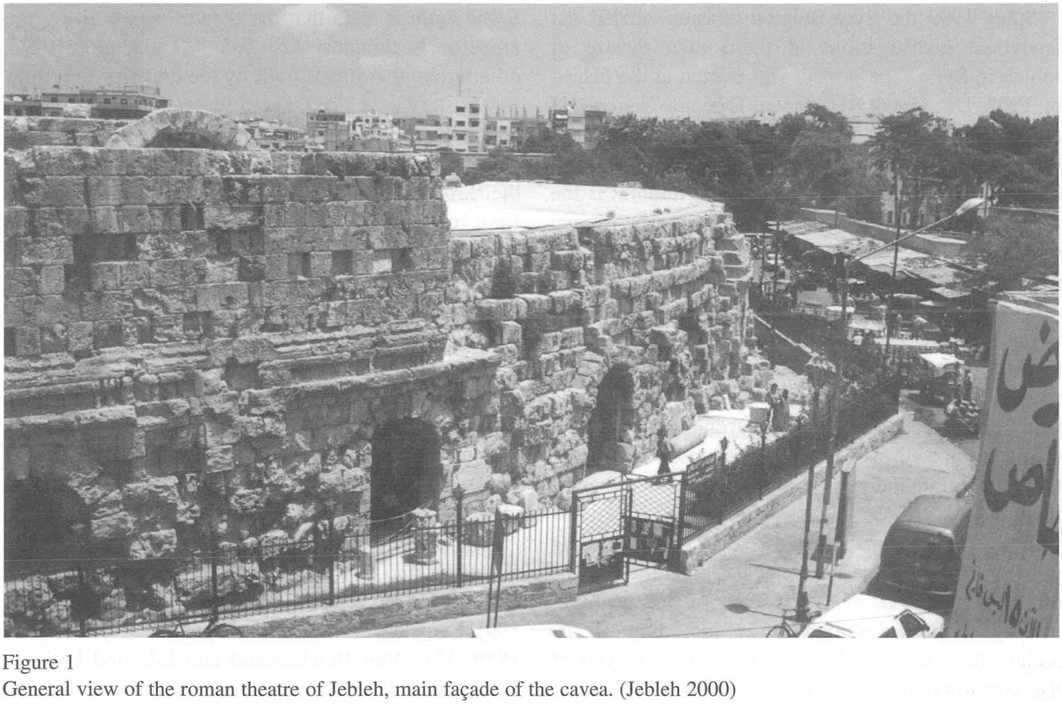

Figure 1
General view of the roman theatre of Jebleh, main façade of the cavea. (Jebleh 2000)

The theatre situated in the centre of the town of Jebleh, is built on a flat land and is orientated to the North. The structure is built in *opus quadratum* with blocks of local sandy-limestone, Figure 1.

Originally, the external façade of the *cavea* was a half circled ring wall where one could see a rhythm of doors, circled windows and buttresses, corresponding to the inside partition of the *cavea* sub-structure. Dividing the levels a profile was running all around the wall and the buttresses, Figure 6, 7. Nowadays on the main façade one can still perceive part of the half circle ring wall. As the street level changed the level of the in-side gallery changed also, around 3,30 meters higher than the original level of the gallery. Original doors and windows are not anymore clearly readable. The lintels of the doors were broken and windows were transformed into doors. Nowadays the existing part of the façade corresponds to the level of the windows, Figure 4.

The façade openings give access to the main gallery with a new travertine slab pavement, built in 1988, and a vaulted ceiling. The compartments in between the radial walls connect the main gallery with a second vaulted gallery. From this gallery is still possible to perceive the starting of another set of *scalaria* to establish the connection to the third level of the *cavea*, Figure 3. The original pavement of the third gallery still exists.

The still standing part of the original theatre corresponds to the *cavea* with its central part relatively well preserved, Figure 2. The *ima cavea* is complete and half of the *media cavea* still exists. Some elements of the *summa cavea* are still in-situ. The three *praecinctium* are still partially visible. The structural system to support the *gradus* is very similar with the structural system of the Bosra Theatre, as well as of some Jordanian theatres (Frézouls, 1952). The relation of the measurements of the *gradus* (height = 0.39 m, depth = 0.65 m, larger = 0.90 m) gives the slope of the *maenianum*, Figure 4, 6. The first arch supporting the second and third *maenianum* is closed with carved stones composing the back wall

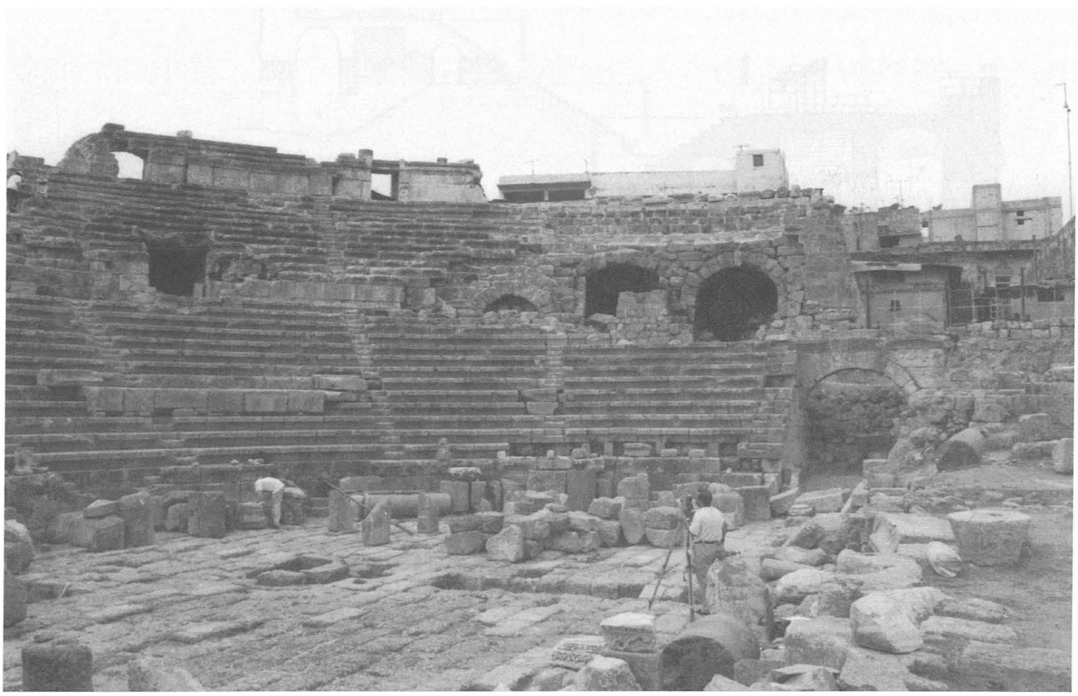

Figure 2
General view of the *cavea*. (Jebleh 2000)

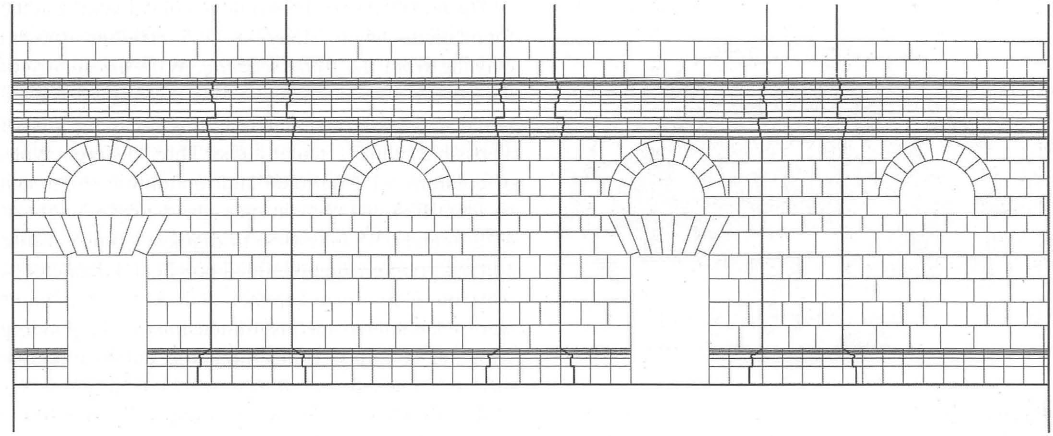

Figure 7
First theoretical reconstitution. First level of the main façade of the cavea. (Saraa Saleh,[6] 2002)

disject; many are still not yet identified. In the town as in the harbour of Jebleh it is possible to recognize architectural elements probably from the theatre.

Materials

Normally a roman builder looks for certain mechanical and aesthetical qualities from stone, and this qualifies the Romans not only to select local materials but also to import stone, sometimes from considerable distances (Adam 1994, 20). As usually, only one type of stone was available in the vicinity of the ancient town of Galaba (Jebleh). Its identification was relatively straightforward. Likewise, the structure of the theatre is built in local sandy-limestone, apart from the *frons pulpitum*, the *gradus* and the *praecinctium* pavement slabs that are made in limestone. The quarries of the sandy limestone were localized in the vicinity of the city of Gabala: one is situated in Shkaifat, 10 km to the north side of Gabala, and the other is situated in Arab El-Mulk, 8 km to the south. The quarries of limestone were situated in the mountains.

The identification of the imported stones obliges to a more complex investigation into geographical origins. The scene building was built in sandy-limestone. The profiled *socle* of the portico of the *frons scaenae* was in sandy-limestone, the colonnade in grey and red granite from Aswan, and the column bases, capitals and entablature in white marble. The origin of the white marble is still unknown; nevertheless the type of marble is similar to the Proconnesus marble, white marble as well white-black veined marble.

Walls

If in Rome the new building material, the roman concrete, was used extensively, the architects of the eastern provinces were slow to adopt the new building methods (Ward-Perkins 1977). The reasons are not only tradition but also because they mostly lacked the volcanic sands, which gave the concrete of Central Italy its unique strength. Their mortar fell short of the quality of its Italians counterparts, and in many areas of the east dressed stone remained the preferred medium for the walls and even the vaults of such buildings as theatres (Ward-Perkins 1977). The structure of the Jebleh roman theatre is completely built in stone. The main structure of the theatre is built in *opus quadratum*, built with rectangular carved blocks made up of local sandy-limestone, arranged in horizontal courses, or ashlars, and with dry joints. *Opus quadratum* is the first development that earns the designation of fine architecture.[2] This is a form, which could give the best stability to the elements of a structure and is exclusively composed by horizontal and vertical lines. The appearance of facings made of rectangular stone blocks can differ quite markedly, depending on a number of factors one of the most important is the arrangement of

the stones in the wall, determining the pattern of the joints. The walls of the theatre, internal and external, follow always the same pattern of joints and the same method of construction through its entire thickness, Figure 6, 7. By the fact that the walls of the theatre are thick —the external façade wall of the *cavea* has 3 m thicknesses average and the interior walls 1.80 m thickness— it was necessary to alternate one course of bonding block laid normally with a course of head-on bonding blocks and stretchers, Figure 1.

ARCHES AND VAULTS

The roman theatre of Jebleh is a complex system of walls, arches and vaulted spaces. The construction forms of the *cavea* are characterised by the intersection of the semi-circular barrel vaulted galleries, ring walls, with the radial segments, radial walls. The segments are on a constant rhythm of radial walls supporting barrel-vaulted rooms and ascending stepped vaults depending of the internal vertical circulation and of the *gradus*, Figure 3. The intersections of the semi-circular walls with the radial segments reveal interesting features concerning the original construction methods. By the fact that the *cavea* structure has a constant rhythm made up of radial walls and compartments it was decided to concentrate the analysis on segments type, Figure 4. Longitudinal sections from the main façade through the main gallery, along the compartments, cutting the *ima cavea* and reaching the *pulpitum* were made. Segment 13.13 —section AA'— characterize the access to the *ima* and *media cavea.* Segment 16.16 —section BB'— characterize the access to the *summa cavea.* Along booth segments detailed cross-sections were made to understand the construction of the vaults and arches as well to verify the stability and deformation of the structure. The study of the construction methods (different stages of construction, why different types of arches were used) gives essential knowledge for a good restoration proposal. This study is still going on; therefore a first analysis is presented.

Arches

All the arches of the theatre are voussoir arches with radiating joints and working at compression. Each voussoir, arch stone, has a trapezoidal section. An important feature is the fact that the extrados and the intrados of the arches are always parallel without any continuation in between the stone arch and the wall.[3] The voussoir arch has de advantage of distributing sideways the loads carried; the loads slide on to the extrados. This type of arch is very useful in networks of large masses of masonry which distributes the thrust to strong points arranged one above another vertically. The arches of the sub-structures of the *cavea* are always making the connection between the radial vaulted galleries and the radial vaulted compartments; they have a rise of 1.90 m and a total of 17 voussoir.

At the main façade of the *cavea* a voussoir arch with 1.10 m rise and 11 voussoirs compose the windows. The doors have as well an arched impost opening, Figure 5. The stone lintel of the door is relieved by the arch, which acts, as a «discharge» above the straight lintel.[4] Very unusual is the arches with a right angle at the extrados of the superior voussoirs so that they fit into their respective courses. This situation happens to make the correction between the superior voussoir of the arch and the cornice.

No marks were found at the spring of the arches, from the façade arches and from the interior arches, that let us suppose the type of centring for its construction. The centring, probably made of at least two arcs of a circle made of wood, joined by a semi-cylindrical base with the moulding of the arch, was probably supported directly on the ground using wooden posts. [5]

Vaults

The Romans were the first builders in Europe to appreciate the advantages of the arch and of the vault (Robertson 1964). It is therefore convenient at this point to remember a remarkable example of roman stone vaulting, the so called temple of Diana at Nîmes,[7] and to remember the remarkable system of stone roofing found in Syrian building of the Imperial age.[8]

When speaking about the vaults of the Jebleh theatre it's important to keep in mind that they are all built in cut stone, dry-jointed and un-mortared. Besides, vaults are individual elements not integrated into the enclosure walls. The general plan of the *cavea* is a half circle, composed by two circular galleries intersected by nineteen segments and

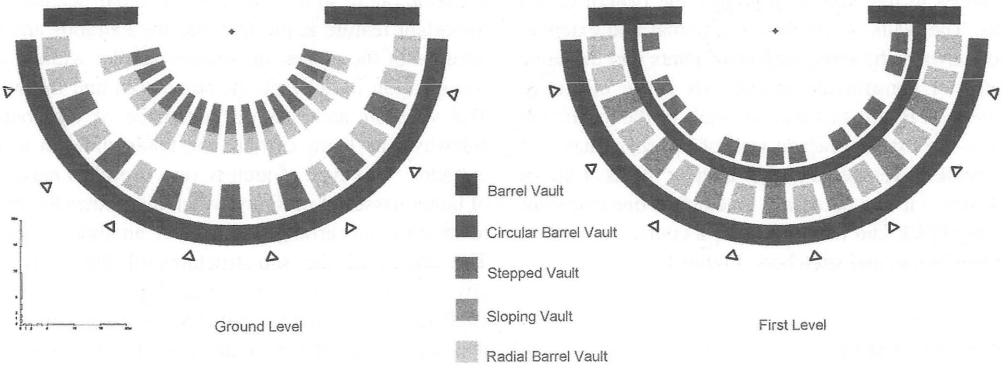

Figure 8
Schematic representation of the relative position of the vaulted spaces. (Teresa Patrício, 2002)

compartments. Different types of vaults enclosed de various spaces, Figure 8. Five types of vaults were encountered: normal barrel vault (this typology was not studied because was only existing at the *aditus*, nowadays in ruins); circular barrel vault, radial barrel vault, barrel sloping vault and stepped vault.

Circular Barrel Vault

The circular galleries, one at the ground level and one at the second level are vaulted. The ground level vaulted gallery, main gallery, has 3.80 m large and a double height of 9.50 m. The vaulted gallery of the second level has 2.50 m large and a single height of 3.67 m. The interesting feature of both galleries is that its section is a perfect half circle, Figure 4, 5, 6.

The builders of the theatre skipped the risk of intersections of the vault and the lateral voussoir arches. At the main gallery none of the voussoir arches of the ring walls intersect the vault. It might be thought that the roman builders, who were familiar with arches and vaults in stone blocks construction, would have overcome this difficult problem by the cross-vault, but this was not the case. On the contrary, the spring of the circular barrel vault is always higher than the keystone of the arches. For the second gallery the situation has more particularities but it will be discussed further.

All along the circular vault, at the level of the spring, a projecting profile with a decorative value as cornice let us suppose that for the construction of the vault the centring was probably supported at the level of the spring, at the level of the last horizontal course, instead of being supported by posts. Roman builders frequently chose this solution, especially if we consider the height of the gallery, Figure 4, 6.

Radial Barrel Vault

We gave the name of radial barrel vault to the vaults enclosing the radial compartments between the two galleries. They compose one of the most interesting vaults of the roman theatre of Jebleh. The spring of the vault is a horizontal line as well as the crown of the vault. However, the span at the starting is larger than the span of the end of the vault. For this reason the cross-section of the vault at the starting is a three-centred arch and at the end is a semi-circular arch, Figure 9. To keep the homogeneity of the joints pattern, that is always horizontal, the number of voussoir changes in both cross-sections: 21 voussoirs for the starting cross-section and 19 for the end cross-section.

For these types of vaults no projecting profile existed as for the gallery vault, yet five squared holes in each sidewalls let us rise the hypothesis of a structure crossing the open space of the compartment providing a robust support for the centring, Figure 4.

Barrel-Sloping vault

The vaulting of the compartments for the stairs leading to the third level of the *cavea* has an inclined

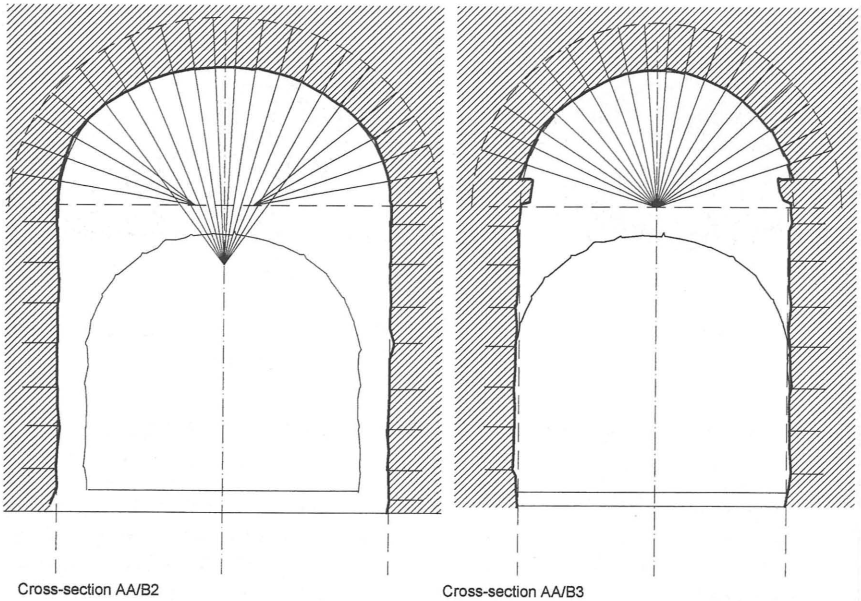

Figure 9
Graphic survey. Transversal section AA', Segment 13.13. Cross-sections of the radial barrel vault, compartment 13.13.B. Cross-section AA/B2 corresponds to the starting of the vault with a three-centred arch; cross-section AA/B3 corresponds to the end of the vault with a semi-circular arch. (Tarcis Stevens, July 2001)

axe elaborating a barrel sloping vault, Figure 10. The fact that the second gallery has small dimensions posed a problem to the builders —the intersection of the two vaults. A cross-vault of stone cutting is not an usual solution for roman builders. The only monument in the Italian peninsula with a cross-vault of stone is the Tomb of Theodoric, in Ravenna built in 530 (Adam, 1994). Moreover, in the case of Jebleh the two barrel vaults meet at different levels, one can only speak of intersection and not about cross-vault. In an attempt to avoid this intersection the starting arch of the barrel sloping vault was slightly inclined to change the level of the spring, Figure 11. As a result, the section of the starting arch of the vault is a parabolic or raised arch.

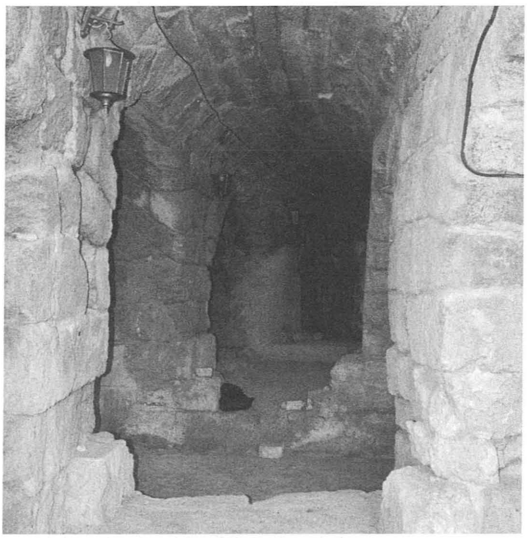

Figure 10
General view of the gallery of the second level of the cavea, at the left side the starting of the barrel-slopping vault. (Jebleh 2000)

Stepped vault

The stepped vaults correspond to the sub-structures of the *maenianum,* that support each *gradus*, Figure 12, 13, and to the substructures of the stairs leading to the

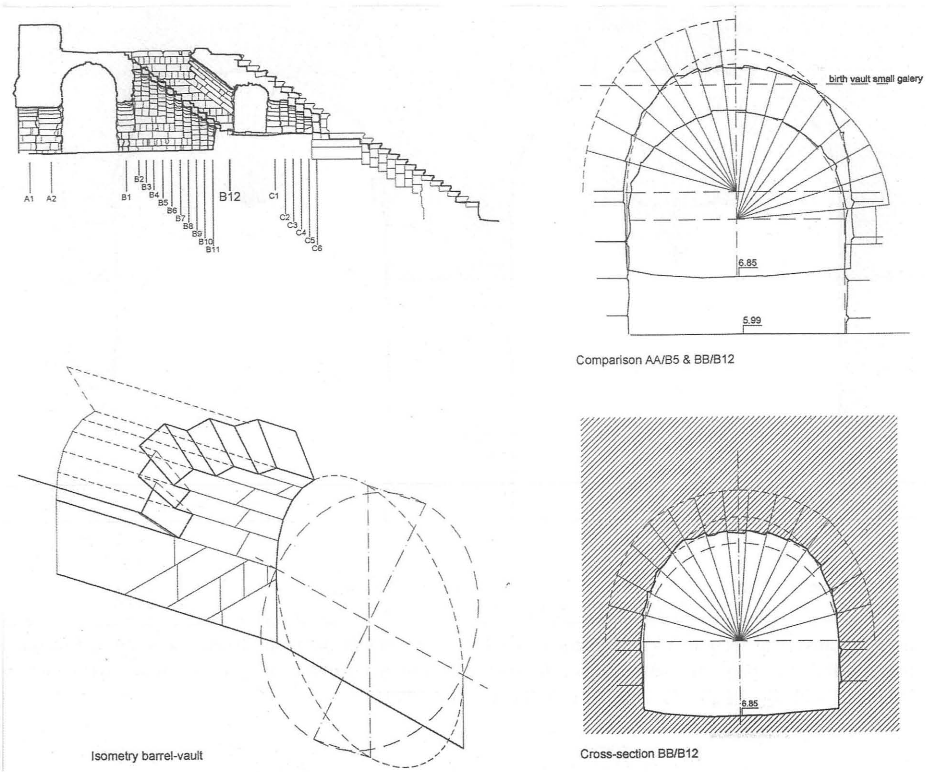

Figure 11
Graphic survey. Transversal section BB', Segment 16.16. Cross-section BB/B12 corresponds with the section of the starting arch of the barrel-sloping vault. (Tarcis Stevens, 2001)

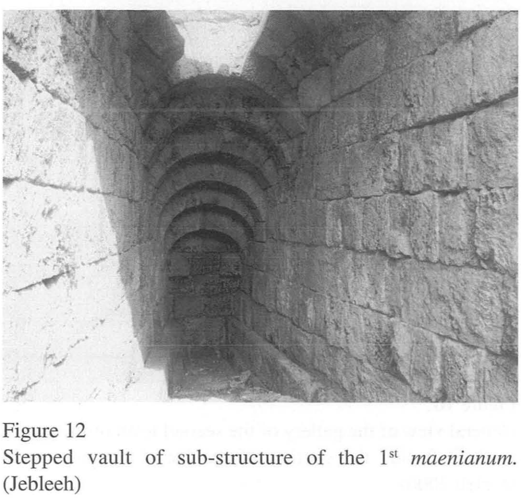

Figure 12
Stepped vault of sub-structure of the 1st *maenianum.* (Jebleeh)

third level of the cavea Figure 14. The vault is formed by an ascending succession of arches developing a stepped vault. Each arch is a voussoir arch that works structurally independent from each other's. This type of vault is very common in the theatres of the region; the best known is in the Bosra theatre.

Final remarks

The results of the ongoing work at the roman theatre of Jebleh are convincing evidences of the importance of the theatre and of the potential of the remains. The technical properties and aesthetical characteristics of the theatre confirm that the theatre is one of the masterpieces of roman architecture in the Middle East. The knowledge gathered justifies the

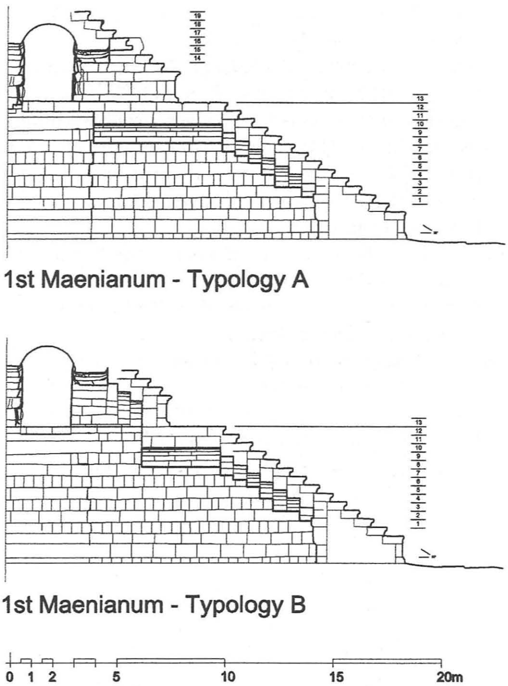

Figure 13
Theoretical reconstitution. detail of the stepped vaults of the sub-structures of the 1st *maenianum.* (Teresa Patrício, 2002)

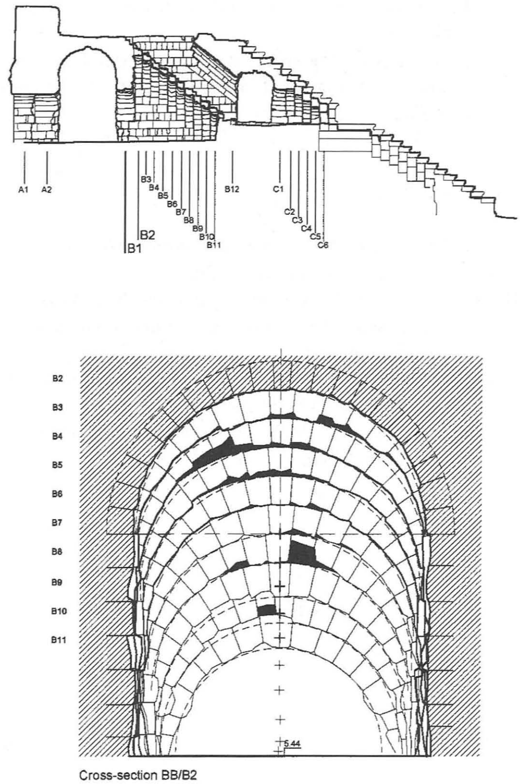

Figure 14
Graphic survey. transversal section BB', Segment 16.16. Cross-sections and projecting view of the stepped vault corresponding to the sub-structure of the stairs. (Tarcis Stevens, 2001)

preservation of the site representing a fundamental step for the global project of restoration and site presentation.

Notes

1. Belgium Programme IPA 5/14, initiated by the Belgian State, prime Minister's Office, Science Policy Programme.
2. One of the first woks of *Opus Quadratum* is the Servian wall, for a long time attributed to the king Servius Tallius, the six king of Rome (578–535), but most certainly built after the taking of Rome by the Gaul's in 390BC (Adam 1994, 106).
3. « . . . Artistically and practically, the integration of a circular shape into a wall created some problems for the stone masons who were confronted with cutting blocks with angled outlines before fitting them onto the extrados of the voussoir. This method of fitting is, however, the most functional, as in this way the arch remains an independent structure from the wall . . . » (Adam 1994, 168).
4. This justified the fact that all the doors lintels were removed in the past without creating structural problems to the façade.
5. « . . . As there is so far no representation in the Roman pictorial record of the building of an arch with centring, no model can be put forward as a precise picture. The only justifiable assumption is that the technique is in every respect comparable to that shown in medieval pictures . . . » (Adam, 1994, 175).
6. Architect Saraa Saleh from Syria; collaborate with the R. Lemaire International Centre for Conservation from the K.U.Leuven, to develop a Master Thesis about the main façade of the cavea. She presented successfully her thesis in September 2002.

7. The date of the Temple of Diana is probably the second century AD.
8. Special group of construction forms extend into the Christian architecture of the fifth, sixth and seventh centuries.

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Presenting Construction History in museums: Bridges in the German Straßenmuseum Germersheim

Eberhard Pelke

The German Straßenmuseum Germersheim (Fig. 1) was founded in 1989 and included in the list of German museums as a specialized technical museum in 1995. The objective pursued is to promote the interest in the history and significance of transport and road engineering in Germany and to keep up further scientific research into that subject. Based on the three phases in the life of a street, namely planning, construction and use, the layman is given an overview of the tasks to be performed in transport and road engineering, while the engineer is reminded of the history of his/her field of work and given an outlook over recent developments.

Figure1
General view on the Dt. Straßenmuseum Germersheim (Photo: Dt. Straßenmuseum Germersheim)

Structure and organization of the German Straßenmuseum Germersheim

The German Straßenmuseum Germersheim was started around 1987 by a small group of engineers of the roads department of Rhineland-Palatinate.[1] Because there was initially no government funding, a registered society undertook the sponsorship. The lack of funds forced the museum society, to concentrate at first on building up a solid base of members —in addition to personal members mainly legal entities (associations, administrations, industry). The commitment of the city of Germersheim, as well as of the state of Rhineland-Palatinate, meant that in 1993, and in a second stage of construction in 1996, the museum could move into the freshly renovated armory in Germersheim, in the end gaining 3.000 m^2 indoor space and about 2.000 m^2 open-air exhibit ground.

Subdivided into the departments of road design, survey, land conservation and design of roadside environment, road construction, structural engineering, highway operations and road maintenance, road equipment, vehicles, machinery and equipment, the German Straßenmuseum presents the visitors with the historical context with the help of numerous exhibits, as well as allowing them to experience technological developments.

In addition to the museum section, the sponsor feels it is important to support research into technical history through an academic department and the

gradual creation of a specialist library. Rooms for lectures and training and further education courses, as well as a Cafeteria round off the picture. Evacuated exhibits are kept in rented warehouses.

The board of the registered society is supported by the competent specialists of a committee and an academic commission. The committee consists of highly qualified men and women from the administration and the business world. The academic commission advises the board in questions of the overall concept, didactics, method and visitor research.

The separate exhibition areas are technically and structurally worked out and realized by unpaid specialist advisors. These specialist advisors are integrated into the museum society through the full-time academic department and a permanent coordinator on the board.

At the moment there are eight specialist advisors in the areas of highway operations, design, structural engineering, road construction, history, traffic, road construction machinery, and road planning.

The museum has about 1.000 legal and natural members. The number visitor per year lies between 10.000 and 15.000.

Department of Structural Engineering

In the department of «Structural Engineering» the development of bridges had to be dealt with.

The armory's massive walls helped in dividing the part of the exhibition situated in the west wing into themes, so called theme boxes. The visitor entering the department of «Structural Engineering» is greeted by two life-sized cross-sections of tunnels in the process of being built. In comparing the light cross-section of the modern New Austrian Method of Construction (NÖT) with that of the 19th century, completely blocked by wooden supports, one can intuitively feel the high level of mechanization and the progress in structural engineering that lies between the two (Fig. 2). The visitors begin their tour with the history of bridges and the area «Statics and Stability», designed by Prof. Dr.-Ing. W. Ramm (Fig. 3). Then there is steel making and steel girder construction (Fig. 4). The mechanization of construction methods with the main types of scaffolding lead to the box on prestressing techniques (Fig. 5) and to the history of reinforced and prestressed concrete (Fig. 6). Short introductions to the bearing of bridges and their expansion joint as well as geotechnics with an emphasis on foundation are rounded off with design and construction of engineering structures. The last two boxes are dedicated to the phases of use of a building. The necessary rehabilitation and maintenance measures, and the continuous supervision to ensure the traffic safety and stability of buildings are described; an official bridge inspection. The museum was able to win a qualified expert from the relevant field of site

Figure 2
Old tunnel cross section under construction
(Photo: Dt. Straßenmuseum Germersheim)

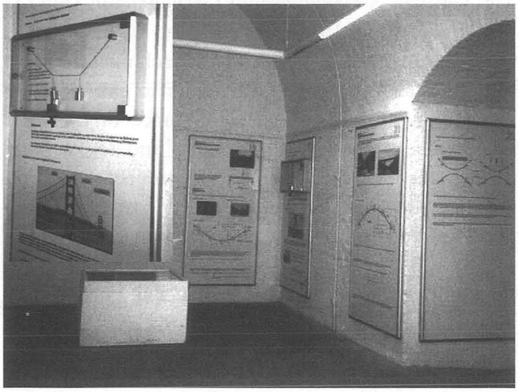

Figure 3
Exhibition box: statics zum anfassen
(Photo: Dt. Straßenmuseum Germersheim)

Figure 4
Exhibition box: steel producing and steel construction
(Photo: Dt. Straßenmuseum Germersheim)

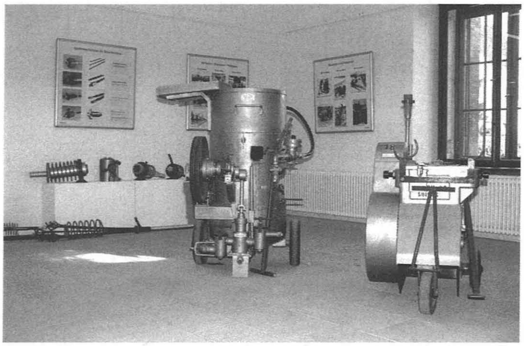

Figure 5
Exhibition box: Prestressing and prestressing systems
(Photo: Dt. Straßenmuseum Germersheim)

Figure 6
Exhibition box: concrete design and construction
(Photo: Dt. Straßenmuseum Germersheim)

engineering for the design and realization of every one of these sections. Sponsoring was necessary for the realization.

GUIDELINES AND CONCEPTION FOR PRESENTING THE HISTORY OF BRIDGES IN MUSEUMS

The guidelines can be separated into those relating to museum didactics, and those relating to questions of transport and construction history.

Museum didactics

To guide the visitors, and give them the chance to process the information at leisure, the exhibition section's structure and design must be subordinate to the concept of the museum as a whole. The exhibition section has traditionally been designed in panel form. The presentation of every bridge is fourfold: The year of its opening to traffic, a contemporary depiction with a subtitle giving the bridge's name, and up to three technical data depending on the type of bridge (max. span l, rise to span ratio, sag ratio f/l, slenderness ratio of stiffening beam v/l), a short text and a portrait of the leading engineer. A graphical panel illustrates the type of bridge and technical data.

Every bridge makes the connection to a technical innovation. The point, however, is not to acknowledge solitary technical milestones, but to illustrate lines of development, which help the visitor to understand today's construction of bridges. The combination of date, contemporary depiction, portrait and short text goes beyond mere transportation of facts and engages the visitors' interest in the building; tells them a little story. The technical begins to interweave with the personal. I refer for example to the deadly accident Albert Gisclard (1844–1909) had with the test train only a few before the official opening of his cable-stayed bridge anchored in the ground near Cassagne (1909) and the courageous jump of his pupil Gaston Leinekugel le Coq (1867–1965) from that same test train.[2] Leinekugel le Cog developed Gisclard's system further, as can be seen in the bridge in Lézardrieux (1924).[3] The portrait of the leading engineer of a given bridge, always accompanied by dates of birth and death, has over time turned out to be indispensable. Especially the

older portraits illustrate the diversity of the designing building engineers' different character and personality. They release the building from its anonymity and, together with the text, enable the visitors to gain a very personal access to the building and the engineering profession.

The exhibition does not force information on the visitors, but gives them space to make their own observations, draw their own conclusions. The observations and conclusions awaken the visitors' interest in bridge construction. The many bridges shown —divided into the four basic types of girder or beam bridges, vault and arch bridges, suspension bridges and cable-stayed bridges— lead the visitors to the three principal stresses on the construction: tension, compression and bending. If they want to expand their knowledge beyond the appearance of the bridge, the illustration, and find the transition from structural constructions to structural systems, then they can continue the exhibition through «Statics and Stability», where they can work out the interaction between the «History of the Bridge» and the mathematical-physical models explaining the flow of forces in structural construction. This part of the exhibition leaves the emotional level and shows the technical facts.

Construction history guidelines

The construction history guidelines as a list of propositions:

- Individual, society and building are connected.
- The building of bridges is connected to the decision by society to create and maintain an intact infrastructure.
- Bridges are a complex detail of the road as a whole.
- Bridges presuppose the will to trade (transport of goods), to exchange information (transport of people), and to gain military strength.
- Because the design of bridges is subordinate to the flow of forces according to the rules of mathematics and physics, the architect cannot create a solitary building, reflecting its designer and builder in person and program.
- The first bridges were not made of stone but of wood.
- Architectural thinking, based on the experience of trial and error, ties the design of bridges to a few forms.
- In the ancient building of vault bridges, the focus must be taken from the Romans and broadened to include the Chinese builders.
- The complexity of their construction meant that no beam bridges were successfully finished until about 1800 AD.
- The diversity of forms, the development of a design palette, has its roots in systematic observation (trial and error) and the development of mathematical-physical models for construction.
- The beginning belongs to the inventors, the development to science. The engineering profession grew out of people from other fields, tinkers and inventors. Only in a second step did the success of way of building become connected to systematic engineering research.
- Technical development begins in obscurity. Small buildings are technical milestones, big buildings are masterworks, the culmination of years of research.
- Beam bridges close the circle of the development of engineer bridges.
- Cable-stayed bridges show the interaction between scientific support and the success of a bridge design.
- Statics and steel allows dematerialization.
- The absence of suitable iron-ore and ironware supported the dematerialization of structuaral constructions in Germany
- This dematerialization shows the way from the beam to the arch.
- Iron and steel forced the transition from the thrust line to the elastic arch and freed architecture from the painful discussion over an adequate vault theory. Adequate parts for the realization of the deflection of the bridge were quickly found.
- Being prestressed frees the concrete of the force to bend and leads to the beam.
- Appearance and construction of bridges reflect developments in society. The paradigm shift from the priority of materials to a priority of the work forces a reduction of forms. «Mass thinking,» as a result of, among other things, a strict interpretation of the economic liberalism

of the 19th century, shows filigree, dissolved frame work structures closely following the rules of statics. The emergence of the labor movement, the gradual introduction of social security systems and adequate wage settlements lead to an investment in mass, and a reduction of wage costs. Rational ways of building, together with a Zeitgeist which longed for quiet forms, meant that the palette of forms grew poorer, focusing the design of bridges on a few successful types, and ending in today's discussion over a building culture in bridge design.[4, 5]

The History of Bridges

The simple, chronological subdivision into three main areas, i.e.

1. Bridges of the ancient world and before
2. Construction of bridges in post-Roman times and bridges in the Middle Ages
3. Construction of bridges from 1750, with the emergence of engineers shows the visitor the close link between bridge construction and the needs of military and trade.

Area I: Wood and stone bridges of the ancient world (up to about 400 AD)

Area I presents the earliest important types of bridges. On the horizontal line, four types of bridges are presented: the wood and stone beam,[6, 7] the Roman semicircular arch and the Chinese arch bridges.[9, 10] Time is shown on the vertical line. This concept of presentation helps visitors to realize that after finding the structural construction, further development took place only in small steps, on the basis of experience. At the end of the line, there is the bridge of Anji, pointing into the future, past area II. With the bridge over the Pyratal in the Vogtland (Germany), the visitor discovers the same bridge construction as the final stage and highlight of vault construction about 1400 years later.[11] On the panel of the Roman semicircular arch bridge, visitors can see that after the development of the arch by the Etruscans, and the invention of cement mortar by Roman architects, the scale may have changed, but the technique did not change significantly.

Area II: Construction of Bridges in the Middle Ages (about 400–1200 AD)

Area II shows, already through its inverse coloring, the decline in the art of bridge building between 400 and 1200 AD as a result of lacking demands on the infrastructure. The revival of the Roman art of the vault by «Bauhütten» and monks is spotlighted.

Area III: The Time of the Engineers (from 1750)

In area III, visitors experiences a time of change, from the builder, craftsman to the engineer thinking in terms of mathematical-physical models. The coordinate system topples. Horizontally, visitors move along a timeline from 1750 to today. Vertically, four basic structural constructions develop:

1. Girder or beam bridges (principal stress: bending)
2. From the vault to the elastic arch bridge (principal stress: compression)
3. Suspension bridges (principal stress: tension)
4. Cable-stayed bridges (principal stress: compression / tension)

The simple arrangement of chronological order and main structural system let visitors discover essential chains of development themselves: Two of these developments are give here as examples:

From the Beam to the Arch

The bridges of the Grubenmann family (Fig. 7), a family of carpenters, are the result of years of building experience.[12] The mixture of arches, truss and frame work indicates an intuitive approach to large span constructions, but also a lack of knowledge about the flow of forces. The Grubenmann's craftsmanship lacked the tools of the engineer. It doesn't admit a clear assignment of force and load bearing member. The beam awaited its engineering instrument in Navier's Elastic Theory (1826). The legendary inventor of the locomotive and railway consultant George Stephenson (1781–1848) was the

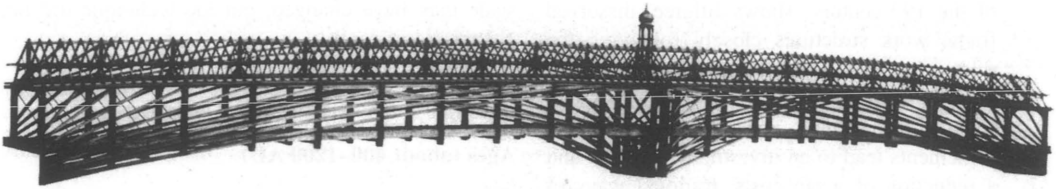

Figure 7
Hans Ulrich Grubenmann (1709–1783): Brücke über den Rhein bei Schaffhausen l = 70,0 m, 1757
(Photo: Killer, Josef: Die Werke der Baumeister Grubenmann, page 26)

first to succeed in a clear assignment of bending tension and bending pressure with the Gauntless-Viadukt (1825) (Fig. 8), a probably an experimental building realized in the course of the world's first railway from Stockton to Darlington.[13] The missing shear regidity was delivered by the Hanoverian architect Georg Friedrich Laves (Fig. 9)[14] The missing understanding of the fishbelly girder suitable for engineers was supplied by Friedrich August von Pauli (1802–1882). He turned Laves' System into a clear, strong system, suitable for heavy loads (Fig. 10), which he could also describe mathematically-physically.[15]

The pressure to create a road network throughout the USA using unskilled labor, without an infrastructure, dependent on materials available on site, resulted in classical architect Ithiel Town (1784–1844) and US army general Stephen Harriman Long (1784–1864) inventing parallel boomed wooden beams, the lattice work (Fig. 11), which could be assembled easily and quickly.[16] William Howe (1803–1852) improved Town's deficient design of

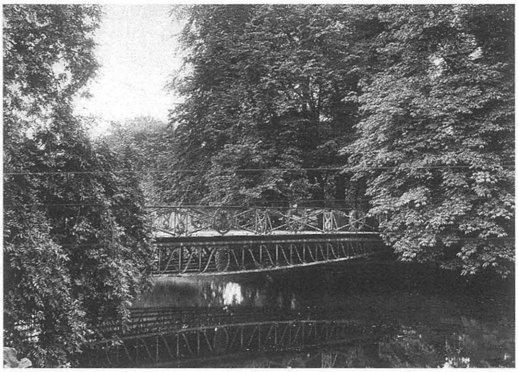

Figure 9
Georg Friedrich Laves (1789–1864): Brücke über die Graft l = 24,5 m, 1840
(Photo: Hoeltje, Georg; Weber Helmut: Georg Friedrich Laves, page 215)

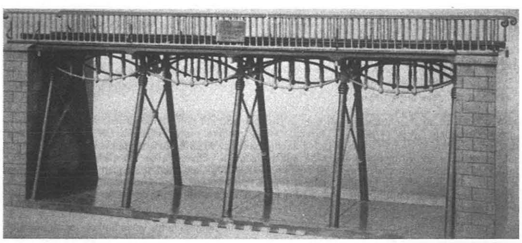

Figure 8
George Stephenson (1781–1848): Gauntless Viaduct l = 3,8 m, 1825
(Photo: Trautz, Martin: Eiserne Brücken im 19. Jahrhundert in Deutschland, page 91)

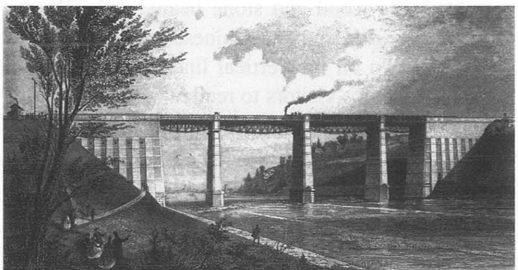

Figure 10
Friedrich August von Pauli (1802–1882): Isarbrücke in Grossheselohe l = 55,4 m, 1857
(Photo: Hilz, Helmut: Eisenbrückenbau und Unternehmertätigkeit in Süddeutschland, page 163)

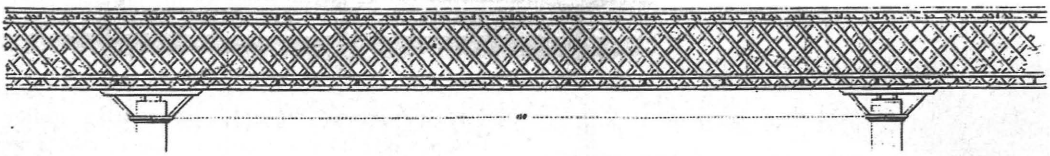

Figure 11
Ithiel Town (1784–1844): bridge over the James River l = 46,6 m, 1838
(Photo: Culmann; Karl: Der Bau der hölzernen Brücken der Vereinigten Staaten von Nordamerika. Allgemeine Bauzeitung Atlasblatt 396)

joints, without being able to significantly increase the constructions' life. The sound politechnical education of the mill-owner's son Squire Whipple (1804–1888).[17] was necessary to move beyond lattice work, which probably went back to the craftsmanship of the Grubenmann family, and had probably been introduced to America by James Wernag, a native of Rietlingen. Squire Whipple, with his patent for «Bowstring» bridge beams (1841) and his instruction book «A Work on Building Bridges» (1847), began bridge design by engineers in the USA (Fig. 12).

Hermann Lohse (1815–1893), Carl Lentze (1801–1883) and other German travelers to England and America,[18, 19, 20, 21] saw the lattice work, and not Whipple, as the decisive impulse. They succeeded in dissolving the parallel boomed iron plate girder in the bearing wall,[22] thereby significantly improving Robert Stephenson's (1803–1859) Britannia bridge,[23, 24] but this German 'special way' had already crossed its zenith after 10 years, with the lattice work bridge at Waldshut (1859) and the Rheinbrücke Kehl (1861) (Fig. 13). Several successors were not able to do away with the system's disadvantages of high use of mass, caused by the parallel girders, and the problematic buckling of the lattice work bridge at the bearing.[25] The paradigm brought home by those who had traveled England and America forced German bridge design to find the way to frame work constructions via the lattice work girder[25, 26, 27] (Fig. 14).

The first iron viaducts in France's Massive Central[28] already show the finished development of the parallel boomed frame work. Gustave Eiffel (1832–1923), chemical engineer and genius at simplifying constructions[29] in the course of four years overcame the lattice work (La Bouble Viadukt) and found in the La Sioule Viadukt the real frame work construction, enabling him to manufacture and assemble in a way suitable for iron (Fig. 15).

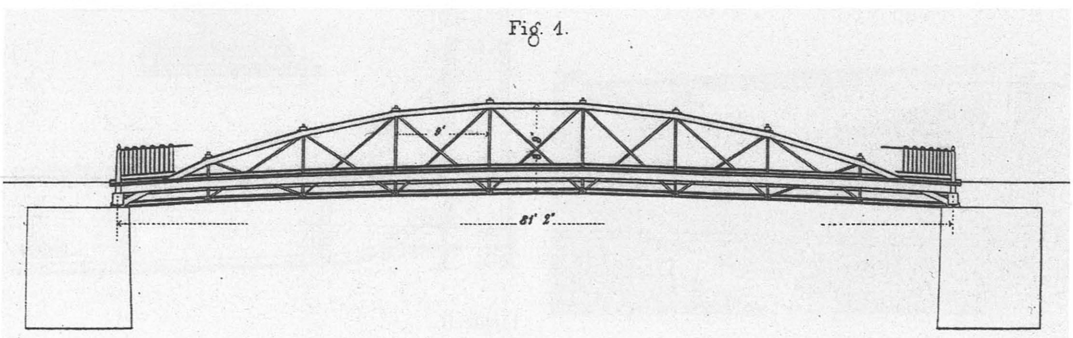

Figure 12
Squire Whipple (1804–1888): Bridge over the canal at Rochester l = 24,7 m, about 1847
(Photo: Culmann; Karl: Der Bau der eisernen Brücken der Vereinigten Staaten von Nordamerika. Allgemeine Bauzeitung, 1852 Atlasblatt 484)

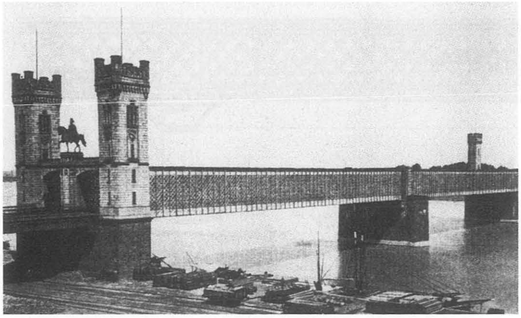

Figure 13
Hermann Lohse (1815–1893): Eisenbahn-und Straßenbrücke über den Rhein bei Köln (Dombrücke) l = 103,2 m, 1859
(Photo: Trautz, Martin: Eiserne Brücken im 19. Jahrhundert in Deutschland, page 68)

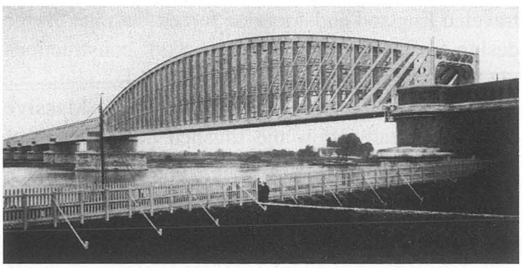

Figure 14
Van Diesen and L. A. Rouppe van der Voort (design) and Brückenbau-Anstalt Harkort (contractor): Lekbrücke bei Kuilenburg l = 157,3 m, 1868
(Photo: Stein, P: 100 Jahre GHH Brückenbau, page 51)

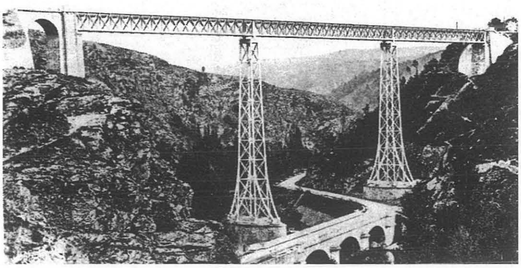

Figure 15
Gustave Eiffel (1832–1923): Viaduct de La Sioule l = 57,8 m, 1869
(Loyrette, H.: Gustave Eiffel-Ein Ingenieur und sein Werk, page 54)

In the race with von Pauli for the minimal use of Mass in railway bridges, Friedrich Wilhelm Schwedler (1823–1894), with the help of his analytical theory of frame work construction,[30] found the way back to Whipple's Bowstring bridge. Schwedler depended not only on the theory of the flow of forces for minimizing mass, he also optimized constructive detailing and supported manufacturing best suitable to iron. In the Weserbrücke at Corvey (Höxter), 1864, the standard of Prussian bridge construction was reached, the statically determinate «Schwedlerträger».[31, 32]

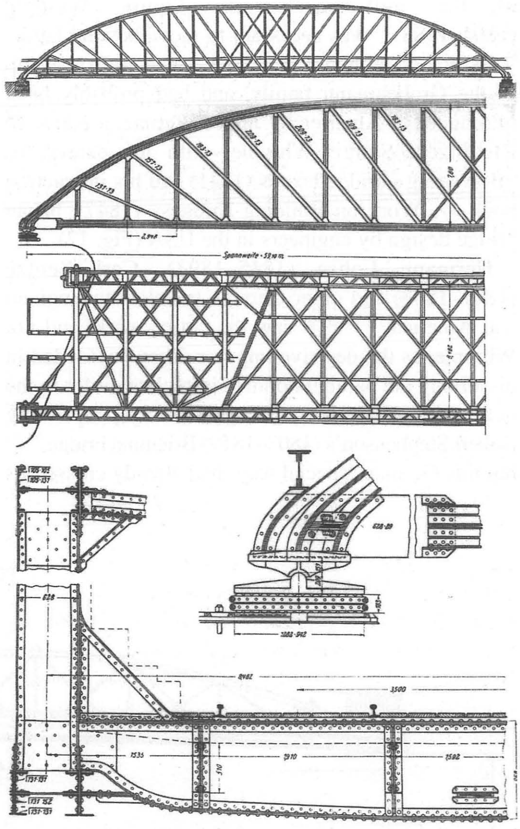

Figure 16
Johann Wilhelm Schwedler (1823–1894): Weserbrücke bei Hoexter (Corvay) l = 56,4 m, 1864
(Hertwig, A.: Leben und Schaffen der Reichsbahn-Brückenbauer Scwedler, Zimmermann, Labes, Schaper, page 17)

Heinrich Gerber (1823–1912), pupil of von Paulis and building site manager for the great Pauli girder bridges at Grosshesselohe and Mainz,[33] overcame the corset of static rules by fixing the centre of moments.[34] His road bridge over the river main at Haßfurt (1867) flawlessly shows the flow of forces in the continuous girder and makes the changing play of forces transcendent through changing intersections of the curved girder (Fig. 17).

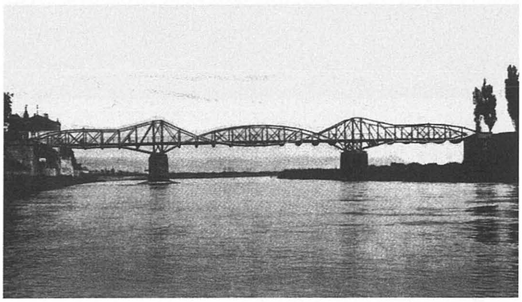

Figure 17
Heinrich Gerber (1832–1912): Straßenbrücke über den Main bei Hassfurt l = 36,3 m, 1867
(Photo: Deutsches Museum München)

The Elbebrücke (1872, 1888) by Hermann Lohse (1815–1893) stands at the end of the dematerialization through girders.[35] By assigning the giders flectural rigidity and through the arrangement of the inserted suspender, Lohse nearly gets rid of the bearing walls (Fig. 18). While the girder statically is a combination between compression and tension arch, the German name «Träger» is based on the definition as transfering the load only vertically to the substructure. Because of their statically indetermination and their vulnerability to restraint forces, the solitary «Lohse Girder», while Popular with the people, remained disputed among experts.

While Johann Andreas Schubert (1808–1870) had splendidly discussed the right theory of the vault using the building of the Götschtalbrücke (1851), Emil Hermann Hartwich (1801–1879) already used the theory of elasticity for the first time in Germany to calculate the arch when he designed the «Alte Rheinbrücke Coblenz» (1864).[37] The bohemian engineer Josef Langer (1816–?) already led the way

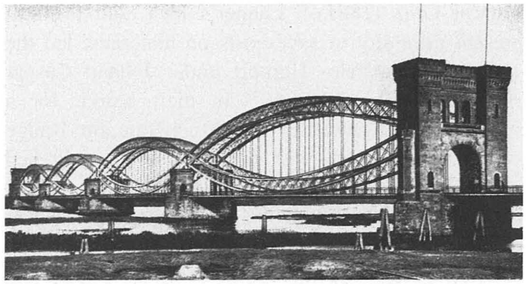

Figure 18
Hermann Lohse (1815–1893): Elbebrücke bei Hamburg und Harburg l = 99,2 m, 1872
(Photo: Mehrtens, G. C.: Der deutsche Brückenbau im XIX. Jahrhundert, page 27)

by combining arches and girders to a highly efficient system.[38] Langer's system, the arch-supported beam, which is still used in bridges today, uses the compression rigidity of the arch with symetrical loads, and skillfully transfers the load of traffic onto the bending resistant trussed beam (Fig. 19). The fusion of horizontal thrust and deck allows Langer's girder to transfer only vertical forces to the foundation, making it universally usable, unlike the normal arch. About two decades had to pass until Langer's girder, with the help of Johann Emanuel Brik (1842–1925), could realize this system in the Ferdinandsbrücke over the

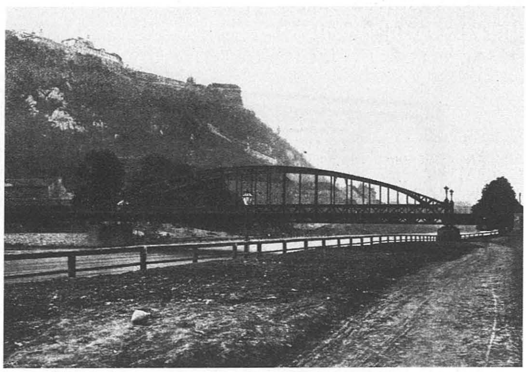

Figure 19
Joseph Langer (1816–?), Johann Emanuel Brik (1842–1925): Ferdinandsbrücke über die Mur bei Graz l = 67,8 m f/L = 1/7,8, 1881
(Photo: Mehrtens, G. C.: Der deutsche Brückenbau im XIX. Jahrhundert, page 29)

Mur at Graz (1881).[39] Langer's idea, and the still present necessity to save costs on materials, led the «Brückenbauanstalt» Harkort under Johann Caspar Harkort VI (1817–1896),[13] in their search for a successor to Schwedler's unit construction bridge system, to the arch with tieback. Harkort's arched girder without horisontal thrust (Fig. 20), unlike Langer's arch-supported beam, transfers the load to the bending resistant arch. The source of this was partly the trend prevalent then to separate road and main structural construction in order to avoid secondary stress, but probably also in the need to find a manufacturable system which can be used with a wider span.[40] The road bridge over the Mosel at Trabach (1899) started the triumph of the bridge system outwardly controlled by statics, which reached its zenith in the Hohenzollernbrücke (1911) over the Rhein with a span of L= 167,8 m.[41] Lang's girder and Harkort's arched girder without horisontal thrust were extreme cases between which today's arch bridges are optimized. By transferring the secondary stress to the bending and using compression as principal stress, they cross the line to the arch and at the same time form the end of the dematerialization of the bending beam.

Figure 20
Johann Caspar Harkort VI (1817–1896): Straßenbrücke über die Mosel bei Trabach l = 54,5 m f/l = 1/6,4, 1899
(Photo: Mehrtens, G. C.: Der deutsche Brückenbau im XIX. Jahrhundert, page 77)

In 1897, the Belgian engineer Arthur Vierendeel (1852–1940) is hired to develop the girder of the future for the occasion of the world exhibition in Paris in 1900. His attempt to find it is represented by the frame girder of Tervueren.[42] The paradigm shift from afficient use of materials to wage efficiency, as a result of a more confident workforce, lets Vierendeel avoid completely breaking the bending down into compression and tension parts, limiting himself to horizontal girders and vertical frame struts, which he connects via bending resistant frame corner (Fig. 21).

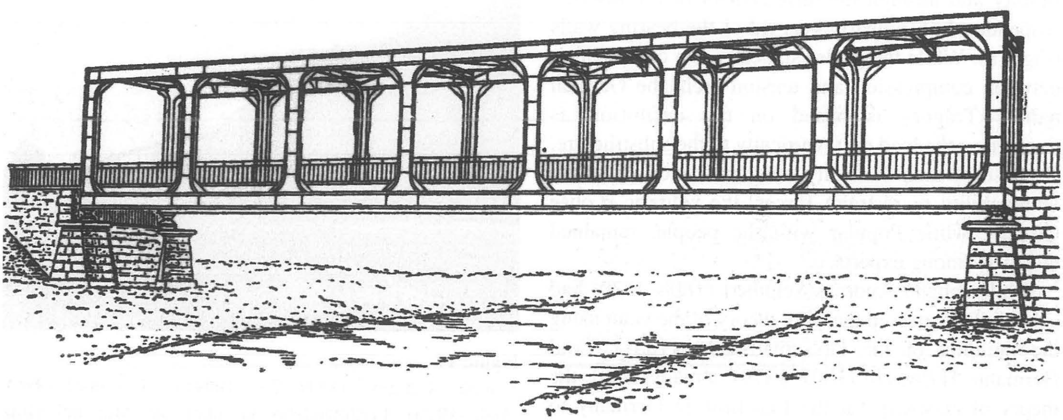

Figure 21
Arthur Vierendeel (1852–1940): Brug over de Schelde te Avelghem, 1904
(Straub, H.: Die Geschichte der Bauingenieurkunst, page 292)

The investment in materials is supported by the turn of the century Zeitgeist, which is looking for calmer forms and wants to let go of the nervous frame work constructions.[43] Virendeel's frame girder still stands, like a symbol, among filegree dissolving frame worked girders and arches, which even the reinforced concrete couldn't resist.[44, 45]

Supported by the new, better quality steel grade and the new assembly technique of welding, the girder succeeds in step by step achieving a wider span. The Mangfallbrücke in the course of the German Autobahn A 8 (Fig. 22)[46] forms the end of a development which puts the arch, despite its efficient use of materials, on the sidelines. While the problems of welding and buckling of the high web plate may not have been completely mastered in 1936, the Mangfallbrücke has the look of many present day girder bridges, which are however no longer dominated by steal but by prestressed concrete (Fig. 23).

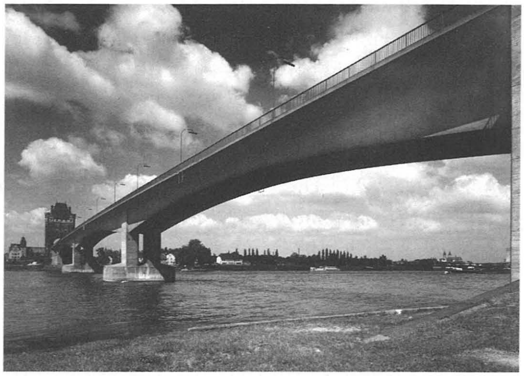

Figure 23
Ulrich Finsterwalder (1897–1988): Nibelungenbrücke Worms l =114,2 m, 1951
(Photo: Dyckerhoff & Widmann)

Prestressing shows concrete the way from arch to beam

In the road bridge over the Dordogne at Souillac (1822)[47, 48] Louis Vicat (1786–1861), engineer Ponts et Chaussées, used artificial limes for the first time. For a rediscovery of concrete, the adition of gravel or stone chippings was needed. This was done by the architect François Martin Lebrun (?–1849) around 1840 in the building of his vault bridge Pont à Grisolles.[49] Both vault bridges were barely noticed; singular works. As is nearly normal in the early history of concrete, it was again a layman, the entrepreneur and son of a matchstick manufacturer François Coignet (1814–1888), who built the first succesfull arch bridges with his béton agglomérés. The structural construction of the drinking water aqueduct in the forest of Fontainebleau (Fig. 24), built from tamped concrete without reinforcement,

Figure 22
Dortmunder Union and MAN AG (contractors): Mangfallbrücke im Zuge der A 8 l = 108,0 m
(Leonhardt, F; Bonatz, P.: Brücken, page 99)

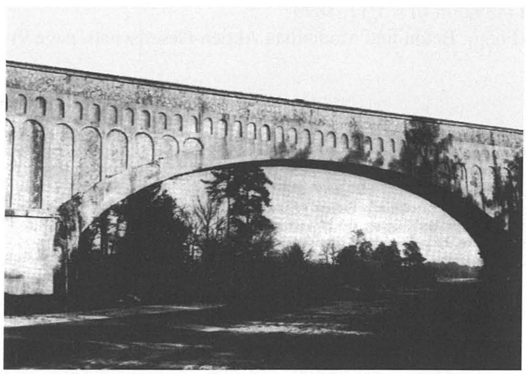

Figure 24
François Coignet (1814–1888): Aqueduc de Fontainebleau, 1867
(Photo: Haegermann, G., Huberti, G., Möll, H. (Hrsg.: Dyckerhoff Zementwerke AG): Vom Caementum zum Spannbeton, Bd. I, page 21*)

clumsily followed the thrust line, like a stone bridge.[50] Only 10 years later, the governmental builder Matthias Koenen (1849–1924) created the first theory for measuring reinforced concrete.[51, 52] Daring and trust in the bending capacity created through reinforcement characterize his road bridge at Wildegg (1890) (Fig. 25).[53] The first successful arch bridge made from reinforced concrete, based on the system of Joseph Melan (1853–1941), was similarly slim, with an iron frame work reinforcement (Fig. 26).[54, 55] François Hennebique (1842–1921) gave reinforced concrete its identity.[56] Hennebique's reinforced concrete bridges all followed the principle of monolythically connecting rib and plate, as the Pont sur la Vienne de Châtellerault (1899) shows (Fig. 27).[47, 57] The initial tendencies towards daring (l^2/f) were finally corrected by Emil Mörsch (1872–1950).[58] In his Isarbrücke at Grünwald (1904)[59] and the Gmündertobelbrücke (1908),[60] a serious rival has been created for steel (Fig. 28).[61] Shocked by his own success, concrete begins to copy steel[3, 45, 62] (Fig. 29).

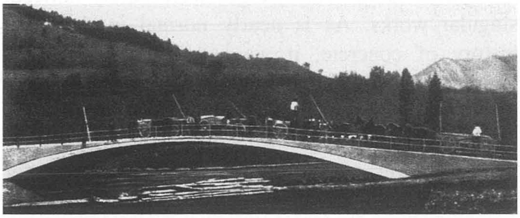

Figure 25
Matthias Koenen (1849–1924): Straßenbrücke bei Wildegg l = 39,0 m f/l = 1/11, 1890
(Photo: Beton-und Monierbau Aktien-Gesellschaft, page 9)

Figure 26
Joseph Melan (1853–1941): Schwimmschulbrücke in Steyr l = 42,2 f/l = 16,1, 1898
(Photo: TU Wien)

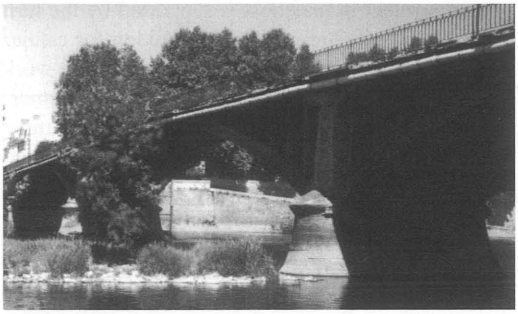

Figure 27
François Hennebique (1842–1921): Pont sur la Vienne de Châtellerault l = 50,0 m f/l = 10,4, 1899
(Photo: Eberhard Pelke)

In the extreme deflection of the vertex (1912) of the Pont de Le Veudre sur l'Allier (1910), Eugène Freyssinet recognized the non-elastic deformation habits of concrete and the necessity of using steel to prestress the concrete.[3] Interrupted by World War I and ongoing projects, Freyssinet used the Great Depression from 1926 to 1929 to develop all important components for the prestressing of concrete. With the prestressing tendon lying in the concrete, following the trust line, Feyssinet freed the concrete from the necessity to form an arch and gave

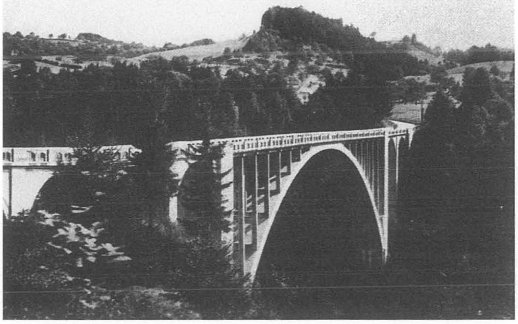

Figure 28
Emil Mörsch (1872–1950): Gmündertobelbrücke l =78,7 m f/l = 1/3, 1908
(Photo: Schweiz. Bauzeitung LIII (1909), plate VI)

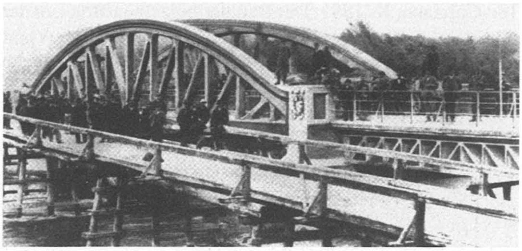

Figure 29
Franz Visintini: Straßenbrücke über Ager bei Schwanenstadt l = 32,2 m, 1911
(Photo: Deinhard, M. (Hrsg.: Dyckerhoff Zementwerke AG): Vom Caementum zum Spannbeton, Band II. Wiesbaden: Bauverlag, 1964, page 58)

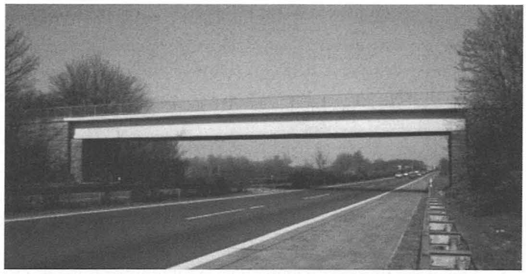

Figure 31
Fa. Wyass & Freytag nach E. Freyssinet: Wirtschaftswegbrücke bei Oelde/Westfalen im Zuge der A 2 (Brücke Hesseler) l = 30,0 m, 1938
(Landesbetrieb Straßen-und Verkehr Nordrhein-Westfalen)

it its form from the beginning (Fig. 31).[64] Prestressed concrete found its way to Germany via Prof. Dr. Karl Mautner, member of the board of the Wayss & Freytag A.G. Germany thanked him in its own way[65] In the race against Freyssinet, Franz Dischinger, working for Dyckerhoff & Widmann, at the same time found the way to the underspanned bending girder via the reproduction of Harkort's girder in concrete (Fig. 30).[66] Around 1990, Friedrich Standfuß came back to the prestressed bending girder with external deflected tendons, and caused externally prestressed concrete box girder bridge to be developed into the standard way of building bridges spanning over about 40 m. The direct relation to Dischinger's road bridge in Aue (1936) is evident. The stringent limits set by the parallel boomed T-beams or box girder begin to dissolve under the aim

Figure 30
Franz Dischinger (1887–1953): Saalebrücke in Alsleben l = 68,0 m f/l = 1/6,2, 1928
(Photo: Friedrich Standfuß)

of flexible adaption to the intended use and cost-effective maintenance.[67] Have the structural constructions of bridges come full circle?[68]

SUMMARY

Engineers are men without history: Fixed on the new, forgetting the old. That is the mirror usually held up to us engineers, or even worse: the image we are proud of. Why, then, a history of site engineering in the context of ongoing projects?

History of site engineering doesn't exist for its own sake. It makes it possible to asses future developments, or recycle solutions from the collection of our predecessors, and to add the missing link to make an old idea work. An awareness of history helps avoid doing the same thing twice, and is a source for ideas.

An interaction of history of site engineering and the development of modern society is necessary. It explains important technical developments, or their lack. In the interest of completeness, especially in the areas of road and bridge building, this second step is necessary.

There is an intact community of interested laymen and experts in site engineering. I have a lot to thank them for. My thanks are especially due to Dr. K. Stiglat, Prof. von Wölfel and his illustrator Prof. K. Nerlich, and many colleagues especially from other countries who spontaneously helped the cause.

What is still missing is an effect on the outside.

Instead, the history of site engineering becomes a fashion propagated by laymen who don't know engineering history, who use it for their own ends[68] without aknowledging the leading function the flow of forces has in design.

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Technological thought and theory, a culture of construction

Tom F. Peters

Apart from the physical role that construction plays in providing technical solutions to problems of insulation, material behavior, and structural integrity, it has an intellectual role to play as a complex, multi-leveled field of concern, a complement to form, space, and function with its own distinct bias. This intellectual aspect constitutes the theory of the field. Theory is an intellectual discipline, an abstract knowledge of the principles of a subject. In construction it cannot, therefore, merely be a collection of solutions or a catalogue of current building practice. It isn't structural mechanics either, which is a comprehensive *method* of calculation and dimensioning rather than a theory. What is it then? If we ask what it is that can concern constructors on an intellectual level we find issues like systems theory, morphology, geometry, problems of scale, perception, ethics (that is: so-called «truth», «honesty», or «integrity» and their contradictions), and aesthetics, which is a philosophical discipline, related to logic. A theory that is made up of these elements is entirely dependent on how a constructor thinks, and so we need to define how technological thought works in order to develop a theory of construction.

The «hard» and «soft» components of technological thought

The special category we call technology is a generic term that denotes a collection of many fields. What they all have in common is that they use a mix of scientific method and empiricism that base on two distinct modes of thinking to make objects that function. Thus technologies incorporate two diametrically opposed views of the world: one hierarchically ordered, and the other, the apparently random pragmatism of technical manufacture. The balance between these two is fluid and can shift suddenly.

Technologists think in ways that differ from other professionals. The physicist and writer C. P. Snow once perceived a cleft between science and humanism, from which he developed his theory of the «two cultures».[1] He considered their differences to be unbridgeable. But the cleft he described is far less drastic than the chasm that exists between these two and technology. As a non-technologist, he was conceptually not sensitized to perceive it. But as builders, we feel this chasm acutely. To some it appears as a hiatus, a basic flaw in our profession, an irreconcilable dichotomy between theory and making, while in others it presents a unique challenge, a drive to create a bridge between them. It is this bridge, this glue between two otherwise incompatible fields that constitutes the uniqueness of technology.

The issue that bonds science and humanism closely together in apposition to technology despite their many differences is their preoccupation with systemic aspects of human knowledge. Scientists and humanists focus on the hierarchical organization of perception, thought, and value, and therefore the

systems they design are always understood to be of a higher order than the elements of which they are composed. Scientists and humanists examine abstractions like concepts, hypotheses, and theories, through which they aim to discover knowledge and gain insight into nature and behavior. Both use analysis although scientists have developed a distinct «scientific method» for thinking using quantitative or «hard» analysis. This thought form is linear and hierarchical in nature and it strives to be «objective» in order to make its paths repeatable to others and thus independent of a thinker's personal characteristics. For that reason scientists are also interested in the method of thought or epistemology.

Matrix thinking, sometimes called empirical, lateral, associative, or intuitive thinking on the other hand, is a multi-dimensional thought-form that can use clear, linear thought tracks like scientific method, but it can also jump back and forth from one path to another using association, and even from one level or scale of thinking to another, for instance from practical problem-solving to broad historical considerations. How it does this depends solely on each thinker's personal interests, value system, or cultural background. Since it is to a great extent subjective rather than objective, matrix thinkers are not interested in epistemology, but they use anything that they find to hand in order to solve problems. Matrix thinking is the creative or «soft» side of technology.

The relationship between system and detail

Technological thought is a hybrid of both the hierarchical and the matrix thought modes with special characteristics borrowed from the one or the other of its constituent parts. In technological thought for instance, the system is frequently less interesting than a crucial constituent part, which makes an object work. This means that the relationship between the whole and the part in technological thought is often incremental rather than hierarchical as it is for instance in scientific thinking. So the phrase «only a detail» is meaningless to a technologist. As an example: the electrical automobile is a banal system. But until we can develop one crucial detail: a battery, which is cheap and light, and can store enough energy, the whole thing remains a figment.

We can attribute this non-hierarchical attitude in technology to the goal of technical endeavor, which is the creation of a functioning object and not primarily gaining insight or knowledge like in science and the humanities. Technologists, when they are working as professionals and not reflecting on their field, rely mainly on matrix thought and only concern themselves with systemic aspects when they verify or refine what matrix thinking has led them to develop. Analysis provides them with controllable input in the form of feedback into their next matrix-driven, inventive thought cycle. In order to develop an object, technologists need to be free to adapt and mix portions of mathematical or scientific theory, or any other means, and to modify them in order to make an invention work. The proof of the correctness of a technological method lies in the functioning of the object and not in its adherence to a theory or in the way it fulfills a formal thought process. Scientists and mathematicians have often misunderstood this lack of «intellectual rigor» as «bastardization» of knowledge or sometimes more kindly, but equally condescendingly, as a naïve misunderstanding of theory and thus «applied science».

In reality, however, technology is far more potent a thought form and even dangerous than this superficial evaluation indicates. The danger lies in the failure to consider the implications of technology, and this is a powerful reason for developing a theory of technology and defining its limits and obligations. Those who oppose technological development call it self-referential and deterministic.

The allegation is serious and an indictment of traditional technological curricula. It is certainly true that technologies such as in-vitro-fertilization or concrete construction raise serious ethical or aesthetic issues. The concerns that opponents raise lie in the lack of consideration of their broader implications by technologists, their clients, and society at large. The very fact that such issues are now considered relevant to technology and that this awareness has spread to unrelated fields as diverse as law, finance, and science testifies to the pervasiveness of the matrix component of technological thought in our world. A century ago there was no such awareness in any field. This fact needs to infiltrate the development of academic, technological curricula. Technologists must be made aware of their form of thought in order to include such broader issues in the purview of the field.

These and many other differences between matrix and traditional, hierarchical thought explain the tension that exists between the «hard» and the «soft» modes of thinking in construction, a tension that lies at the heart of all creative thinking. Some thrive on this tension and are energized by it, while others, the more non-creative thinkers, avoid it as painful. It is the tension caused by the combination of these two so different forms that makes technological thinking so vital. The «hard' component analyzes and the «soft» component synthesizes. Together they contribute to making functioning objects.

Translation and Transformation, a matrix method

Like the «hard» side encapsulated in scientific method, the «soft» side of technological thought also has its concepts and methods. Until now they have been less studied. I've looked at two of its concepts that I call «translation» and «transformation». The first, *translation*, moves information between fields and the second: *transformation*, applies it from one object to another within a field. These two concepts determine how we operate as technologists, and they are directly applicable to both design and construction. The method both translation and transformation use is to shift our standpoint. This shift occurs when a linear thought pattern suddenly jumps from track to track or level to level in matrix thinking. When and where in a thought process this occurs is partly subjective and culture-dependent. The cultural dependency is easiest to demonstrate in the use of language, because different linguistic traditions, which can be professional or cultural, have different concepts and names for objects.

The German language, to take an example from engineering construction, distinguishes between the «Platte», a planar structure that resists out-of-plane forces in bending and the «Scheibe», one that resists in-plane forces in shear (Figure 1, 2). These terms are not identical to the English «flat plate» or «slab», and «shear wall». Whereas the English terms primarily indicate the structure's spatial orientation and its function as a floor or a wall, the German terms do something else. They only define the way the two types of planar structure carry their loads. This explains, for instance, why Robert Maillart had an easier time inventing his remarkable bridges made of

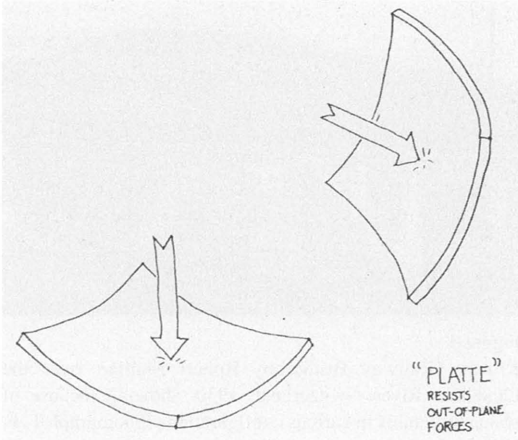


Figure 1
«Platte», or planar structure that resists out-of-plane forces (diagram T. F. Peters)

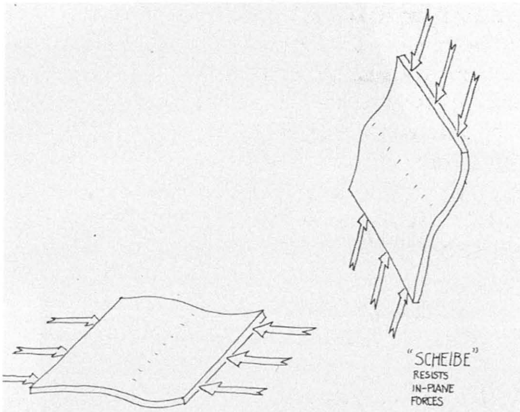


Figure 2
«Scheibe», or planar structure that resists in-plane forces (diagram T. F. Peters)

planar structures (Figure 3) because he spoke German than he would have had if he had spoken English.

Based on the shifts that engender such differences we can more readily understand how translation and transformation work. In 1830, the foundry master Karl Ludwig Althans built the Sayn Foundry in Bendorf, Germany, a little-known masterpiece of nineteenth-century iron construction (Figure 4). The

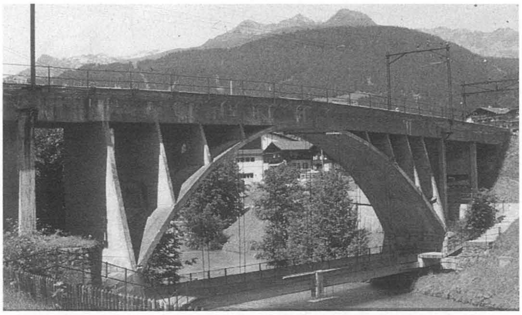


Figure 3
Klosters Railway Bridge by Robert Maillart over the Landquart River, Switzerland, 1930, showing the use of planar structures in various configurations (photograph T. F. Peters)

Figure 4
View of the façade of the Sayn Foundry by Ludwig Althans in Bendorf, Germany, 1830 (photograph T. F. Peters)

multi-leveled complexity of this machine-building is one of its interesting features, but the one I want to stress here is the way Althans used transformation in his structural innovation. If we look at the truss supporting the gantry crane that carried molten iron from the furnace mouth to the casting floor (Figure 5), we see that it rests on a fishbelly truss. The fishbelly truss was only patented about ten years later, so in order to invent it Althans had to draw on other models he knew. The cast I-beam was one, and he used it for the compression chord. Gothic tracery was another, and he used that for transferring shear between the top and bottom chords. But the most remarkable feature, and the one that really demonstrates transformation, is his use of a gigantic, laminated wagon spring made of hand-made crucible steel for the tension chord of his truss. We can only understand the magnitude of Althans's invention if we remember that the very concept of a truss still lay twenty years in the future.

Another transformation was Althans's use of cannonballs, one of the foundry's products, as ball bearings for the swiveling derrick cranes, which rotated around the columns of the casting floor (Figure 6). Again, ball bearings would only be patented in France 27 years later in 1857, so Althans had nothing to build on as a model, and he certainly could not have designed his cranes the way he did if he didn't have ball bearings.

Althans used translation in the façade and the clerestory of the casting hall (Figure 7). Although the tracery reminds us of Gothic church design more than anything else, we get our clue from the diagonal

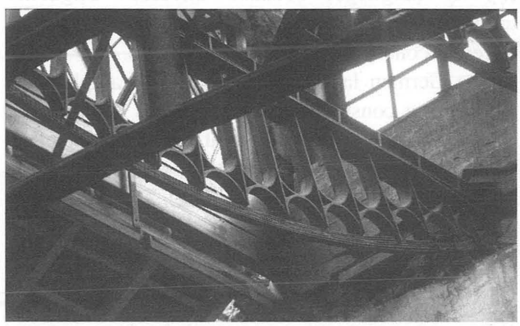


Figure 5
View of the composite fishbelly truss made of cast iron and steel that supports the gantry crane in the Sayn Foundry, 1830 (photograph T. F. Peters)

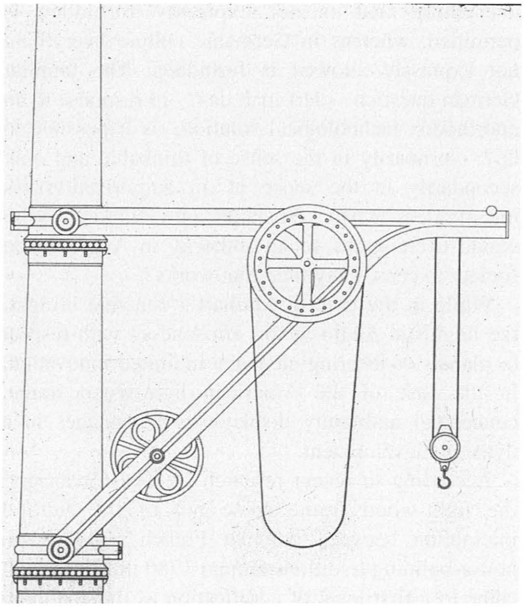


Figure 6
Elevation of the swiveling derrick crane attached to the columns of the Sayn Foundry using cannon balls as ball bearings, 1830 (drawn by Zarli Sein)

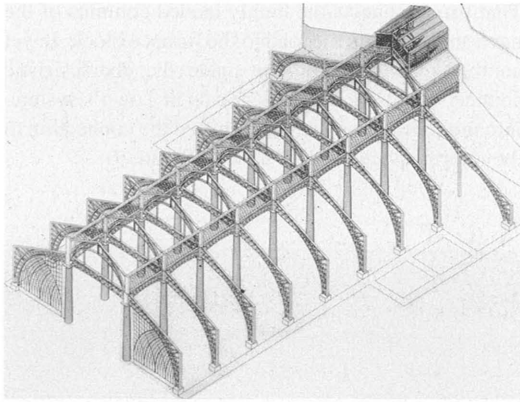


Figure 7
Axonometric drawing of the iron stucture of the Sayn Foundry, 1830, showing a Town Truss stiffening the façade and the clerestory, 1830 (drawn by Zarli Sein)

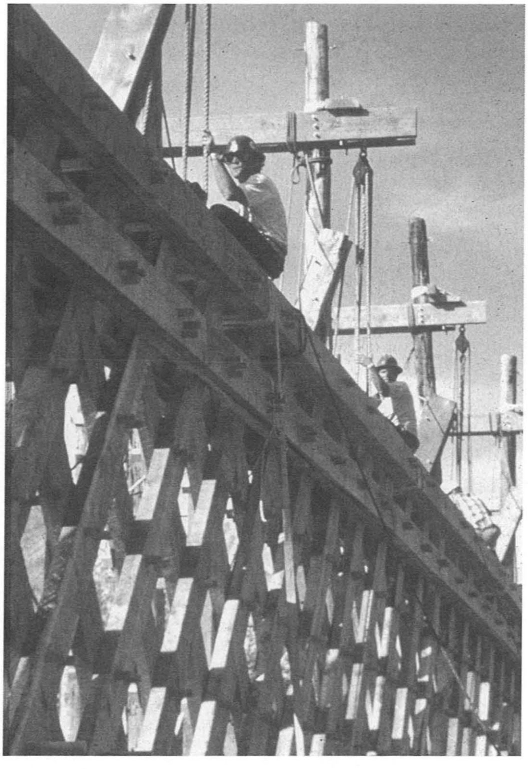


Figure 8
Reconstruction of a Town Truss, the Speed River Bridge in Guelph, Canada, 1992 (photograph Ken Rower)

stiffening of his fishbelly truss. Ithiel Town had patented one of the most useful prefabricated and standardized wooden bridge types in the US in 1820. The Town Truss (Figure 8) was made of one cross-section and one type of connection. European engineers were interested in its potential and would soon transform it from wood to iron. But even before they did that, Althans translated it from a bridge into a shear panel, a truss, and a bracing mechanism for his highly stressed, cast-iron foundry hall. The hall had to withstand heavy loads rolling dynamically back and forth and swiveling to and fro on the framework, and so the frame is braced laterally and at the back by the massive masonry walls and the furnace block. However, in the glazed front Althans needed further stiffening. The crisscrossing gothic tracery of the Town Truss served his purpose well. And the small-scale panes of glass he inserted in the open interstices of the truss transformed the truss into a shear membrane, not a «shear wall» but a «Scheibe». Althans did the same for the clerestory.

That truss connects the highly loaded columns of the nave and transfers the load to the furnace block. In yet another transformation, he made the characteristic connection points of the diagonals in Town's system, into monolithic castings, and shifted the connection to the interface between his panels (Figure 9).

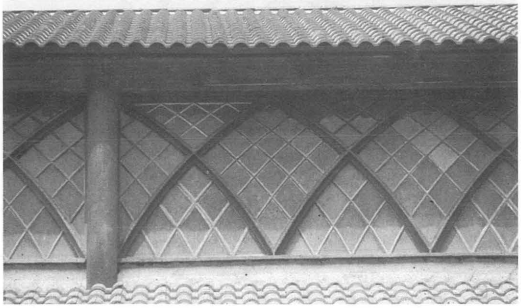


Figure 9
Clerestory trussing of the Sayn Foundry, 1830, showing connections between the panels instead of between the ribs (photograph T. F. Peters)

THE ADVANTAGES OF AMBIGUITY: THE LIGHT-WOOD FRAME

Shifting standpoint gives rise to ambiguity, and ambiguity is another pragmatic and non-hierarchical concept that characterizes building thought. Practitioners have developed pragmatic as well as conceptual approaches to construction, The pragmatic come from the «soft», synthetical mode of thought, while the conceptual stem from the «hard», analytical mode. Stereotyping is always an exaggeration, but in order to characterize the two approaches culturally I called them the «Anglo-Saxon» and the «Germanic» approaches, simply because each culture assigns particular value to one of them. The anti-conceptual, «Anglo-Saxon» attitude to construction is characterized by pragmatic invention. By adopting this approach we are invariably led to the unanswerable: «Why not?» in response to the query whether or not something is possible, rather than to recognition of the subtleties of cultural rules and intellectual limitations as does the more conceptual approach. In Anglo-Saxon culture, the saying goes, everything that is not expressly forbidden is permitted, whereas in Germanic culture everything not expressly allowed is forbidden. The familiar German question: «darf man das?» in response to an unorthodox technological solution, (is it possible to do? —primarily in the sense of thinkable and only secondarily in the sense of an authorization), is meaningless when translated into English. Who would exercise the social authority in Anglo-Saxon society to censor anything that works?

While in the case of Maillart's concrete bridges, the linguistic Anglo-Saxon «fuzziness» with respect to planar loadbearing elements inhibited innovation, in the case of the American light-wood frame, conceptual ambiguity displays its advantages in a dynamic development.

According to recent research by Ted Cavanagh,[2] the light-wood frame arose out of the cultural interaction between colonial French and English house-building traditions around 1780 in Missouri. It came to a first level of codification as the «balloon-frame» or «Chicago construction» in Chicago between 1830 and 1850 and to a second one as the «Western platform frame» on the American West Coast a century later in the 1940's. Today, the frame still dominates American residential construction, which accounts for over 80% of American construction activity.

The light-wood frame is ambivalent in nature and bears little resemblance to a traditional timber frame (Figure 10). It can be regarded structurally either as a panel that is stiffened by ribs or a thin stick frame

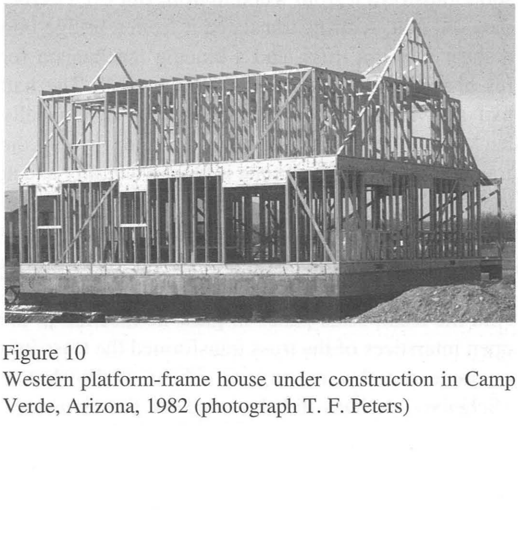


Figure 10
Western platform-frame house under construction in Camp Verde, Arizona, 1982 (photograph T. F. Peters)

made rigid by surfacing. If we regard it as a panel system, certain ground rules involving penetration, interface of elements and connecting apply, and if we regard it as a frame it manifests other boundary conditions. But thanks to the ambivalent nature of the system, a builder can mix the different criteria without concern for conceptual distinctions. This leads to a plurality of possibilities in spatial and formal organization, and that has guaranteed the system's popularity over two centuries of use.

The nail increases the degree of ambiguity. Because the simple connector is spread evenly throughout the object, it works by virtue of statistics, that is: through quantity, rather than through its quality (Figure 11). The pragmatic contractor's solution is always to use more nails whenever faced with a complicated connection problem. In other words, the behavior of the individual nail under stress and the quality of its function as a connector is of secondary concern. It is rather the quantity and the pattern of its distribution throughout the object that is important.

Figure 11
The simple nailed connection of a light-wood frame relies on the number of connectors rather than on the quality of each nail (photograph T. F. Peters)

Figure 12
The lashing of a traditional southern Chinese bamboo frame used to be in bamboo strips. Today it is made of plastic tape (photograph T. F. Peters)

This «statistical» characteristic is rare but not unique. We find it in the early North American «proto-trusses» developed for road and railway traffic, and there is a parallel in the bamboo scaffolding of Southern China where lashings replace the nails (Figure 12). The builders of light frames and bridges were unconcerned with the quality of the connection and with the capability of the workman who made it. Instead, they relied on many connections. The bamboo frame had severe typhoon loads to withstand, and this meant paying more attention to connection quality. Nevertheless, it too relies on the large number of connections spread throughout the frame (Figure 13).

The statistical nature of such connections renders this type of structure quasi monolithic. A nailed or lashed frame can transmit forces in any number of unanticipated ways (Figure 14) as long as the basic rules of the panel-cum-frame are respected. There are, of course, limits that cannot be exceeded (Figure 15).

The invention of the Balloon Frame, how it affected architecture in the New World. The case of Chile

Marcela Pizzi

The Industrial revolution and its' consequences in the Architecture of the New World

Industrialization in Europe takes place at the end of the XVIIIth century, when due to the invention of machines, manual labor is substituted to elaborate raw materials like iron and animal or natural fibers like cotton, wool or linen.

Associated with this there is a need of colonial expansion in search of raw materials which triggers a race between the leading European countries, such as the Netherlands, France, Spain, Portugal and especially England towards the dominion of new territories in the world. The British Empire is the leader, and its' influence has affected the culture and image expressed in their architectural expressions, of remote countries such as Australia an New Zealand, Hong Kong, India and the American Continent.

Clear expressions of the influence of the British Empire are present in the United States, which suffered a direct process of colonization, in the Caribbean and the major ports, as well the Southern tip of South America due to the development of a sheep station industry.

Wooden Building Technology in the United States during the XVIII and XIXth century

We will focus on the invention of the balloon frame system of construction in wood, an invention of the American continent, which allowed the population and dominion of unexplored areas in a relatively short period of time.

In the American Continent the European inventions were rapidly introduced changing the need of specialized craftsmen who were scarce.

Post and Girt system.

Before the invention of the balloon frame construction with wood was slow and required skilled labor based on mortised and tenoned joints.

In colonial times, wood was used in its' simplest form, building walls of horizontal logs, either left round or hewn square, developing several systems of log corner notching to strengthen the crucial junction.

Far more common then the horizontal log walls, are those in which spaced vertical members provide structural support. The earliest is the medieval post and girt system imported from England and France by the first colonists, in which heavy corner posts and widely spaced intervening posts carry the upper loads. Heavy cross —timbers carry upper floors, which are unsupported by the thin internal walls below. All the structural joints are laboriously hewn into interlocking shapes and held by wooden pegs.

This system dominated the English and French colonies and persisted after the American Revolution.

Braced Frame System

With the availability of increasing abundance of commercial saw lumber relatively inexpensive

Some references credit him as the inventor of the balloon frame, such as Andreas in his «History of Chicago» in 1890 and in» Industrial Chicago» in 1891, the most important book on the development of Chicago. He is also mentioned by the architect J. M. Van Osdel, who arrived to Chicago in 1837, in an article, «The History of Chicago» published in a Chicago monthly, in which he mentions Snow as being the inventor of the balloon frame and being this construction method had superseded the earlier framing system.

In Giedion's opinion in 1941, the first balloon framed building was St.Mary's Church in Chicago, built in 1833 the earliest catholic church in the city. Old carpenters adverted that it would collapse, and was razed and erected three times.

In 1924 Walker Field in his article «A reexamination into the invention of the balloon frame», written for the Journal of the Society of Architectural Historians, attributes the same church to Augustine D. Taylor.

Later in 1981, Paul Sprague , establishes that indeed George Snow is the first one in using the balloon frame technique a year before Taylor, (1832) not in the St.Mary's Church , but in a warehouse.

The system is widely used in the west coast, were the use of wood as a building material was practically unknown, except by the Russians or the Yukon Indians, until 1835 in California. Thomas Larkin, a native from Boston started to build in wood in the city of Monterey, two story houses with balconies, using the Massachusetts cabin as precedent, an unknown typology in the area.

Larkin applied a two story verandah as a means to protect the adobe built houses from erosion, also unknown before his arrival.

Until the seventies the new system was called «Chicago Construction» and was presented in the form of a farmhouse which was sent in sections at the Paris Universal Exposition of 1867.

The inspiration for these houses, were the seventeenth century farmhouses of the early settlers.

The expansion of balloon framing in the world

The adoption of balloon framing system helped the consolidation of cities, not only by the speed and costs of building in wood, which allowed the shift of societies from an agricultural dependence to concentrated ones in based on cooperative and specialized division of labor. It literally change the image of the places in which the angloamerican culture either landed, or merged with the local conditions.

Especially interesting is the case of India, were the wooden technology had to suffer a process of adaptation to a warmer climate crating new spaces, which were later carried to other places in the world.

A clear example of this is the incorporation of intermediate spaces like the verandah, the courtyard or the open livable roof, space typologies, taken as far as Australia and New Zealand, Hong Kong, the Caribbean, Argentina, Peru and Chile.

Even new materials were used in other parts of the world, such as corrugated iron for siding, originally used in China, a material ideal for siding in places were wood was scarse.

The intense commercial activities of the British Empire done buy clippers, and the development of coastal cities, needing shelter for a rapidly increasing population, was a perfect situation for the easy and ready balloon frame system.

The main style associated with balloon framing is the Greek Revival, and became a symbol of the New World. It was first used to express the independence from Europe, in which the United Sates with the creation of a new Republic looked in the origins of democracy.

The style, according to Talbot Hamlin, in his book «Greek Revival Architecture in America», dominated the east coast of the United States between 1820 and 1860, and in the west coast due to the gold rush from 1840 to 1880.

The case of Chile

We will illustrate through the case of Chile, to what extend the balloon frame structure reached and transformed the architecture of even remote places of America, through commercial activities.

We will present two very different cases in Chile, which clearly reflect the enormous influence in the image of the built environment, due to anglo american commercial activities searching for raw materials.

The first case is coastal city in the desert in the

northern part of the country, were a port, Iquique, built in wood, in Greek revival style, using balloon frame technology with wood brought from Oregon as ballast in the ships. The white gold rush, as the natural nitrates were called, attracted a large number of immigrants with need of shelter.

The second case, totally different in its' origin is the development of sheep stations settlements in the southern tip of South America in the Chilean and Argentinean Patagonia. This time the British searched for large pasture lands for sheep herds coming from Australia and New Zealand through the Falkland Islands.

Case Studies

Iquique

The port of Iquique dates previous to the Spanish domination, and presents its mayor population growth due to the commercialization of nitrates with Europe and the United States, in the XIX[th] Century, between 1883 and 1919. Nitrates were used as a fertilizer and later as a component of gunpowder. Previous to this founding the British exploited nitrates in Egypt and India in de XVII Th. and XVIII[th] centuries.

According to Charles Darwin, the first shipments were sent to France and England in 1830.

The opportunity of becoming rich in a short period of time attracted a great number of immigrants, among which carpenters and builders built structures for shelter using wood brought as ballast which was left in the beach once the nitrates were embarked.

A singular architecture was produced in the desert, which had to suffer a process of adaptation to the new local conditions, which we will describe in detail further on.

Greek Revival the style used, becomes popular with the United States of America independence, as it evoked the birth of democracy. Another reason for its' popularity is the discovery in 1804 of the Athens Parthenon by Lord Elgin, and emphasized Greece as the mother of Rome.

The war for independence carried out in Greece in 1821, attracted sympathies in the United States, and from the 1830s. The use of Balloon Framing imposed a style.

It propagated through Pattern Books, especially those of Asher Benjamin, such as «The Practical house Carpenter» and «The Builder's Guide», or those of Minard Lefever, «The Modern Builder's Guide» or «The Beauties of Modern Architecture», or that of Andrew Jackson Downing, «Cottage Residences».

Almost all the Pattern Book authors took their material from the English Peter Nicholson.

Through Pattern Books, it became possible even to order a complete house, with was shipped and easily put in place with simple tools upon arrival, a precedent of prefabrication.

They were shipped to the West Coast or South America, through Cape Horn.

An increasingly large number of architects trained in the Ecole des Beaux Arts and the United States started to use Greek models, in designs of high quality, such as Benjamin Latrobe, Robert Mills and William Strickland and his disciples.

In the south of the United States, balloon framed structures was used in Ante Bellum mansions with French precedents.

One important aspect of the Greek Revival style developed in the United States is that it is the first style in presenting its shorter facade towards the street. Fig 3

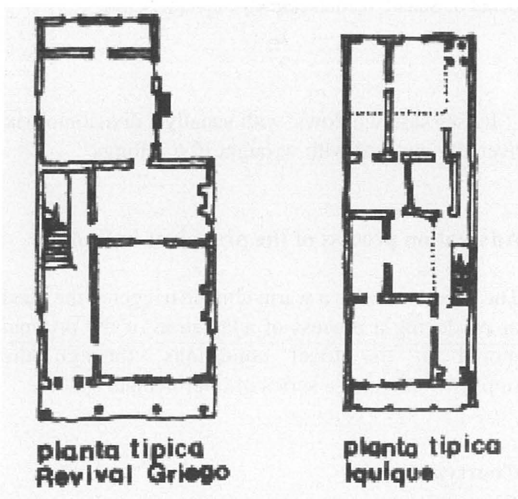


Figure 3
Greek Revival Plan in US and Iquique, Chile

The use of columns is a characteristic, but with the invention of the balloon frame, those of square section, cheaper and easier to build, were applied. This feature is exclusive of Greek Revival, balloon framed architecture in the New World since it doesn't exist in Greek or roman precedents, nor is present in Greek Revival structures in Europe. Fig 4

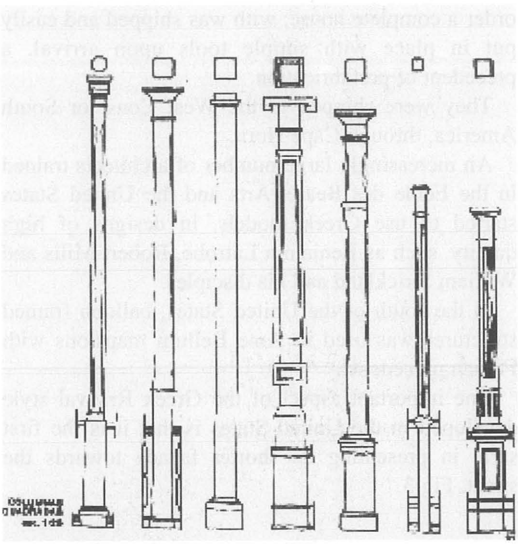
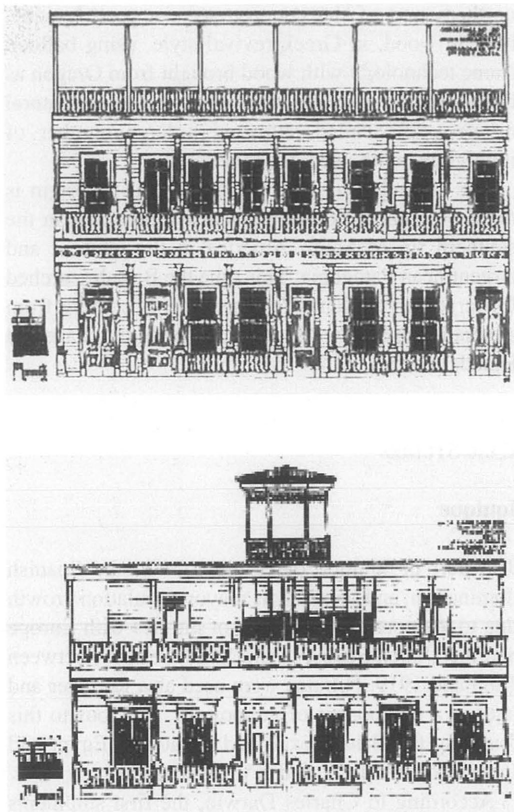


Figure 4
Detail of Square section columns, Iquique, Chile



Figures 5 and 6
Wooden Balloon Frame Houses in Baquedano Street, Iquique, Chile

It uses sash windows, with usually a division of six over six, covered with wrought iron railings.

Adaptation process of the precedent in Iquique

The encounter with a warm climate triggered the need of producing a process of adaptation of the original model to the local conditions, through the implementation of a series of intermediate spaces.

Courtyards

Greek Revival houses were usually freestanding structures in the United States, but in the case of Iquique they were built as continuos structures to avoid hot unshaded spaces as it was not possible to have gardens as water was scarce.

Courtyards are taken from the previous Spanish influence to allow natural light into the rooms and creating an outdoor space.

Verandah

The verandah is applied to the architecture of Iquique creating an intermediate space between the fresh inside and the heat outside. As a consequence a new area was created for leisure of the family, which sat in the afternoons to watch the passers by.

The origins of this element, are not clear, but apparently is a consequence of the encounter of this type of architecture with warm climates, taken from India.

The use of the verandah is especially interesting in the port of Iquique, forming a, continuos facade.

Open roofs spaces

This is one of the most interesting aspects of the architecture of Iquique, because of its' uniqueness and gradual evolution.

A double roof with a space in between, which would allow the air to flow and thus refresh the house below is added. With time this space began to grow in height until it became useful for carrying family activities, as an outlook to see the ships approaching the coast or for laundry.

These double roof spaces are also present in India, were it is used for sleeping, but apparently the presence of this element in Iquique, does not relate to this influence, an appeared spontaneously.

Wooden treatment

Wood does not have a good performance in dry climates as the desert, so a protection system had to be developed in this new context. In the case of the roof, this was covered with clam shells, with its' convex side receiving the humidity of the morning fog and thus avoid damage to the roof boards.

In the case of the facades, these were protected with stucco and painting them with bright colors such as orange and blue. Fig.7

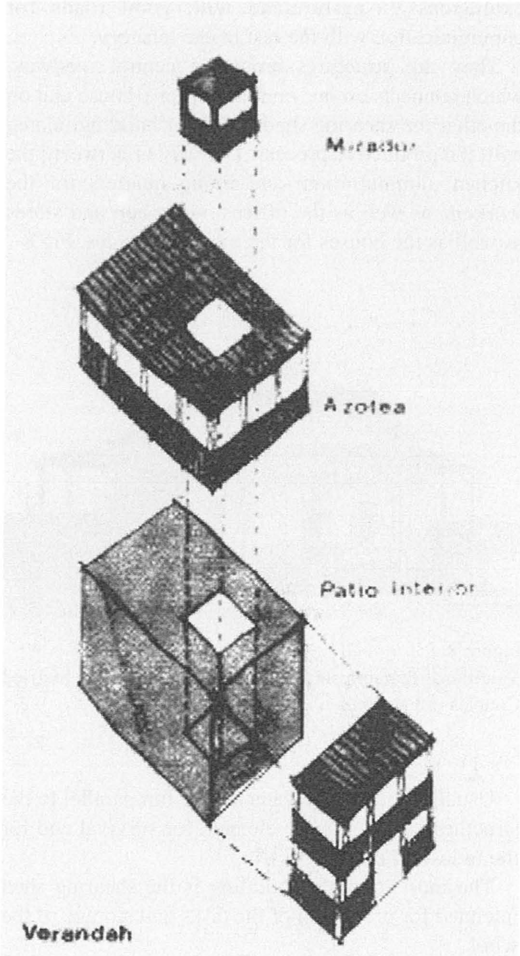


Figure 7
Elements of Greek Revival Balloon Frame model adaptation to climate in Iquique

Sheep Stations in Patagonia

The occupation of the farther tip of the American Continent known as «Patagonia», took place in the decade of 1880s giving origin to a surprising sheep raising enterprise, developing an non existent architecture in Chile associated to the process. The British Empire searches for large territories for pastureland, to supply the required amounts of raw material needed for the newly industrialized wool industry. It is how this singular architectural expression is developed in Australia and New Zealand, which will become the industrial and architectural reference of the Chilean and Argentinean case which arrives to the area through the Falkland or Malvinas Islands. This singular expression responds clearly to the necessary conditions for sheep raising, giving an industrial character to the settlements.

It is important to describe the layout of these settlements, usually located in the center of large

extensions of pastureland with good roads for communication with the rest of the territory.

They are structures around a central roadway, which connects on one end the owner's house and on the other the shearing shed and other building related with the productive process. Halfway in between, the kitchen, dinning room and living quarters for the workers, as well as the offices, workshop and stores as well as the houses for the married couples. Fig.8

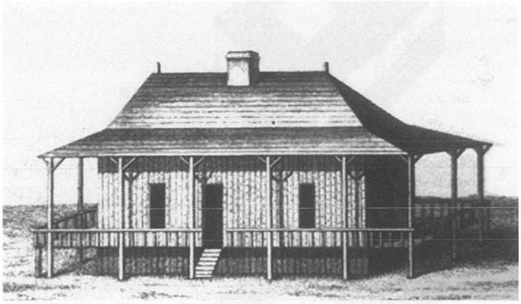


Figure 8
Traditional Prefabricated Balloon Frame House for Married Couples in Patagonia Sheep Stations

Usually a course of water would run parallel to the structuring road, a basic element for survival and for the industrial process.

The most important building is the shearing shed intended for protection of the tasks and storage of the wool.

The first examples were only basic open shed made with logs as structural system raised from the ground to allow the droppings fall into the ground. It was divided in three areas, a central one for the sheep to be sheared, another on one side, with good light, where the shearing process would take place, and a third on one on the front area where the wool would be classified, pressed and stored. Fig.9

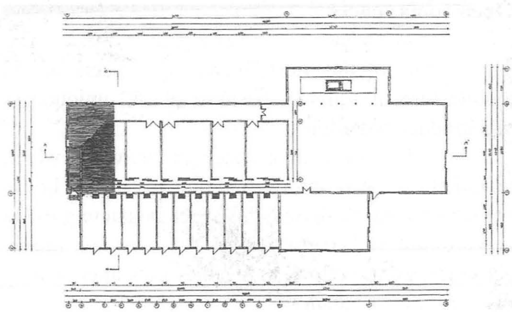


Figure 9
Shearing shed, Río Verde Sheep Station, Patagonia, Chile

Towards 1880 the Worseley scissors are introduced, which because of mechanization gave more speed to the process, and allowed the rationalization of the shed, locating a mechanized guide on one side. Here the shearing process would take place, which was connected, to an engine, which gave way to another building beside the shed, the Machine House. Fig.10 & 11

Due to the profits gained industrial sheds are carried out, considering the use of wood and galvanized iron as siding, system invented in England

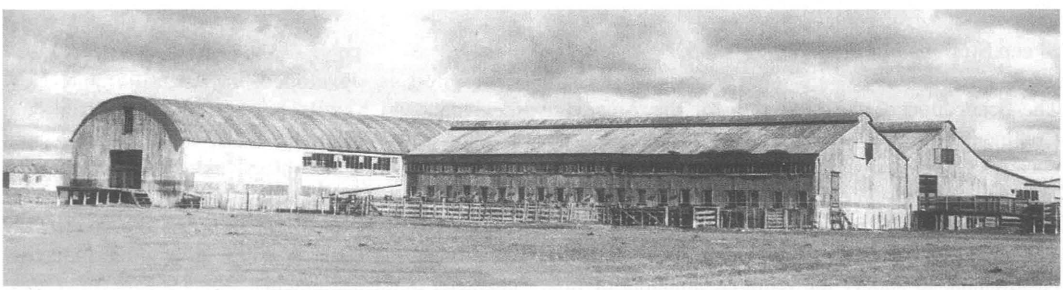


Figure 10
Shearing shed Ciaike Sheep Station, Patagonia, Chile

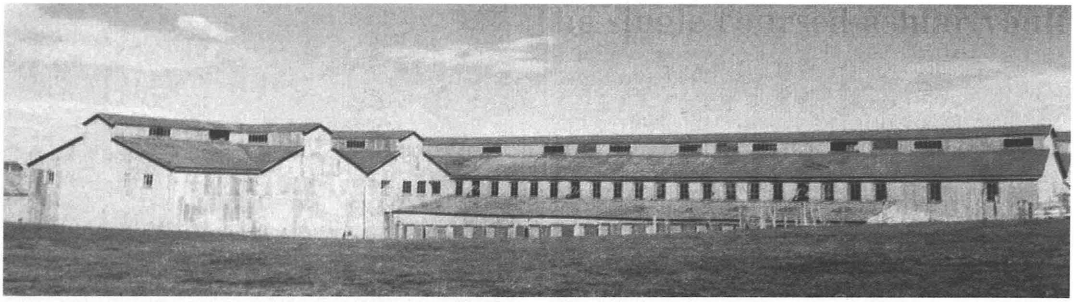


Figure 11
San Gregorio Station shearing shed, Patagonia, Chile

at the beginning of the XIX[th] century used for storage sheds in the Liverpool docks, probably due to encounters through trade with China.

The Building System

The first elements, which appeared in the settlement were all those buildings required for the industrial process, housing therefore was left for later.

The first shearing sheds were small in dimensions and usually prefabricated, which later grew in dimensions due to the large sheep herd, but maintaining its plan and original functionality.

The building has its' precedent in the English «rick», a prefabricated structure in galvanized iron used for the storage of garden tools, which was raised from the ground and posed over concrete or wooden posts, which allowed a space underneath were the animals could seek for shelter if needed. Fig. 12

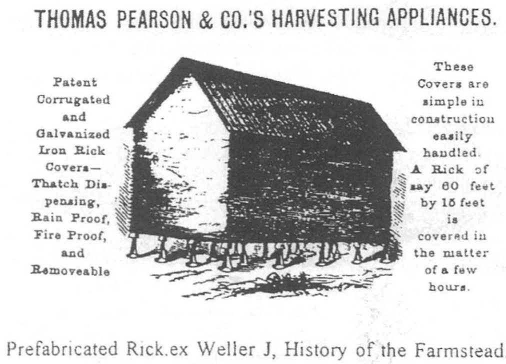


Figure 12
English rick, as appeared in the local press, XIX[th] century, England

At first, wood was used for the shed's siding, being quickly changed for galvanized iron, which gave the definitive image to this architecture, a wood frame of regular pieces, covered by corrugated iron, on its' walls as well as roof, a system which allowed to raise these buildings quickly. They were finally painted for rust protection, which made the sheep station identifiable through its color. San Gregorio Station for instance in yellow and red.

The structure was based on regular pieces of native wood, using the balloon frame technology brought from the United States. This system was a tremendous progress for the region, which until that time used wood for construction based on the Hispanic technology with post and girt technology joined with leather, wooden pegs or notched. Fig. 13 & 14

Conclusion

The invention of the balloon frame technology, together with industrialization, allowed America and all those areas which the Anglo-American culture encountered either through colonial or commercial activities, the development of settlements and sovereignty of unexplored areas in a relatively short period of time.

Together with this process an architectural image was expressed in a series of very different contexts around the world, were a new revolutionary building

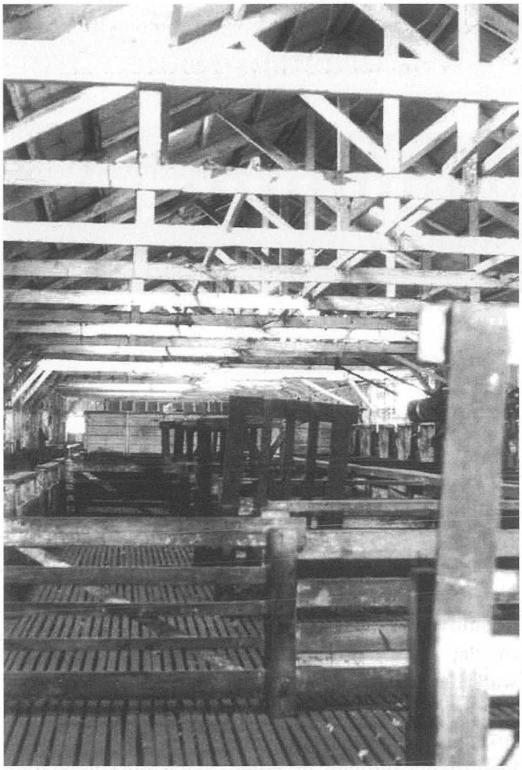


Figure 13
Interior Shearing shed in Oazy Harbour Sheep Station, Patagonia, Chile

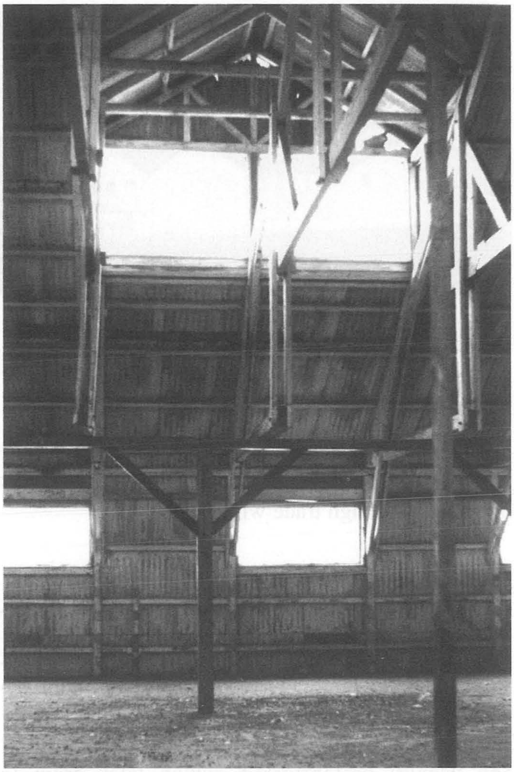


Figure 14
Interior Shearing Shed Caleta Josefina Sheep Station, Patagonia, Chile

system was developed, together with the associated style of the time, the Greek Revival. Its' invention in the United States and its' expansion through the rest of the world in the XIXth Century is an important contribution not only as part of the history of construction but also in terms of image and character with which it was associated.

We have presented two very different cases one in the desert and one in a climate of extremes. In both we can see that the expression is not coherent with a geographical division, the architecture of Iquique is also present in coastal cities of Peru, and the Patagonia Architecture related Chile and Argentina in the same expression.

More so, these expressions nowadays have become part of the heritage of each of those countries, which we should be preserved for the future.

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Who did what: Division of labour among construction-related firms

Christopher Powell

This conference is a welcome new international opportunity to link and compare hitherto separate bodies of knowledge. So this study takes as its subject something common to all buildings, regardless of date, site or function. Rather than being about buildings themselves, the study stretches construction history to include the means of building. It asks how the various processes in building were divided between producers: who did what? This intangible organizational question is best explained by examples. Many buildings were created by single firms doing virtually all the work themselves. For instance, some nineteenth century UK builders undertook to do almost everything from designing to brickmaking, to plastering interiors and all the rest. Elsewhere and at other times many a building was built not by one firm but by uniquely assembled groups of many separate firms. One thinks, for example, of eighteenth century craft tradesmen in London or Bath, each project with its independent bricklayer, carpenter and so on. As will be shown, sometimes single integrated firms did the work, and other times groups of divided firms did it. The endlessly varied business of building shows great diversity in industrial organization among firms, with wide national, regional and market differences.

Questions are posed about how different divisions of labour between firms emerged in different historical contexts. Why were, say, masonry and other craft skills integrated in a unified firm in one place and time, but remained independent and separate in another? Why were materials processed by the builder here, but by independent materials suppliers there? Why did builders' merchants, as a separate trade, split off from raw materials producers? Why was responsibility for design separate from construction here, but combined with it there? How did owners of firms choose between combining different trades or specializing in a single one? In short, why did boundaries between business entities differ and shift? Were changes arbitrary or were they rational responses to particular conditions?

Before looking at detail, it is worthwhile glancing at modern fields outside construction. Division of labour between non-building firms is often interestingly fluid: for example in retailing one trend is integration, away from divided, specialized high street shops and towards supermarkets. Elsewhere, insurance companies, airlines and other big integrated firms move in the opposite direction, towards division. Some now divide their functions by subcontracting computing or customer telephone services to new specialized firms located remotely in, say, India. In terms of industrial organization, there are issues here about the advantages and disadvantages of specialization and scale of firm: control, agility in responding to change, economies of scale, labour costs, vertical integration along supply chains, and so on. The context of each industry, as

well as its own internal culture, play a part in deciding division of labour among firms.

This short study aims simply to examine, by means of case studies, a range of divisions of labour among firms in various periods of construction history and to review some possible determinants of division of labour. The term «firm» is taken to refer to an independent business entity, whether small master, partnership, joint stock company or other formation. The term «division of labour» is taken to refer to that aspect of industrial organization to do with the distribution of building-related processes between separate firms. The summarized case studies following relate mainly to the part of the industry which produced large higher quality works. Regrettably, most of the examples have had to be drawn from UK rather than wider historical experience.

Renaissance Florence

The first of four snapshot case studies, in chronological order, is of building in fifteenth century Florence, based on the admirable study of Goldthwaite (1982). Renaissance Florence was, of course, architecturally precocious to an unusual degree; in mid century a prosperous pre-industrial city of perhaps 40 000 people, in which institutions and wealthy individuals were gripped by a propensity to build.

Much demand for building stemmed from rich private individuals using accumulated wealth to build urban palaces for their own enjoyment. They engaged closely with the construction industry, often employing the necessary labour as salaried employees and (fortunately for us) they kept very detailed accounts. Goldthwaite tells us that accounting was so elaborate as to be «almost as impressive as the palace itself» (a reminder that heavy paperwork is not solely a modern bane). Sometimes materials or labour were contracted for, but mostly only on smaller works. Generally, lack of capital among craftsmen, operatives and materials suppliers discouraged an entrepreneurial role among them, and obliged the building owner to employ direct labour. A purveyor of the works was directly employed on large projects, such as the Strozzi palace which took about fifteen years from 1489, by up to one hundred workers. Purveyors of the works, who had a clerical or administrative rather than craft background, made arrangements for materials supply, checked deliveries, took charge of financial administration, made payments and kept accounts. This financial administrative role was complemented from the craft side by a foreman of the works, either full or part time depending on project size. He had supervisory powers to co-ordinate the workforce although, as noted, they were employed on independent terms by the building owner. Design work was headed by an architect, although his role was more fluid and less clearly defined than it later became. Often the architect was paid as a sort of part time consultant. Materials supply was the responsibility of the building owner who obtained bricks, sand, lime and so on from independent producers through the market. Where steady supply was wanted contracts might be made, although the business climate held an accepted notion of «fair price». Site work was carried out by direct labour «wallers» (Goldthwaite's term for skilled builders in stone, brick, roof tiles and plaster) and «stonecutters» (hewers, scapplers and sculptors). Wallers were independent workers who each headed a small gang of an assistant and one or two labourers usually paid by the building owner rather than by the waller who directed them. Wallers often worked in association with each other, but not in formal partnership. Goldthwaite points out that they possessed most preconditions for becoming contractors in a modern sense, except credit and willingness to organize labour.

The Florentine industry may be summed up as a fragmented one in which the building owner played the key integrative role as direct labour employer. Below him was a small tier of senior people, the purveyor of the works, architect and foreman. The site workforce was of direct labour wallers, stonecutters and labourers, and materials were obtained largely through independent producers. The owner kept close overall control and could stop or redirect works virtually overnight if he chose.

Mid-nineteenth century London

The second case study is of London around 1850, based mainly on Satoh (1995). Greater London was a large city (nearly 3m. population) whose vigorous

growth was powered by early industrialisation. Demand burgeoned for new commercial, industrial, institutional and residential buildings in new and traditional forms.

Much demand came from capitalist enterprises investing in building for gain (and maybe glory). The industry was led by large general contracting firms owned by individuals or partnerships such as Cubitt, Grissell and Peto, and Myers. These firms contracted with building owners for erection of whole buildings, having submitted competitive bids, typically on the basis of independent architects' designs. That profession had gradually distanced itself from builders and was likely to be paid directly by the building owner. General contractors employed all, or nearly all, the traditional craft trades of stonemason, carpenter and so on, enabling them to do virtually all the work themselves. Small specialized works (such as stonecarving or gasfitting) might be subcontracted to independent specialist firms answerable to the general contractor. Subcontracting was constrained by building owners' and architects' distrust of unreliable firms (which abounded). A sound reputation was important to general contractors, who needed to trade on their ability to integrate the various crafts needed on large projects. To rely on subcontracting, due to slenderness of means or other reason, was to deal with a shady commercial world of small struggling firms, poor quality work and worse. Despite this, some rather furtive subcontracting was done from time to time, where possible with firms with whom the general contractor had already worked. The big general contractors were substantial concerns: as early as the 1790s Alexander Copland had employed up to 700 on urgent military projects. By 1850 some firms were said to employ one, two, or even three thousand. Most were casually employed, but it appears that a few key skilled men were found continuous employment. Management structures are not well understood, but appear to have been divided into men directing workshops and yards, those overseeing site work and those with overall responsibilities. These three groups were also subdivided by craft trade (such as slater or plumber). Firms occupied their own well-equipped yards and workshops for storing and processing bulk raw materials such as timber and stone: independence rather than reliance on other firms was the aim.

General contracting was far removed from Florentine building practice. The key role had shifted from building owner to general contractor. Under his direction were grouped nearly all the necessary craft skills: division of labour was minimal and integration and control were at a premium. Specialized firms were confined to the margins, being limited to occasional and semi-covert assistance to general contractors (and humble small works). The large integrated general contractors met a market preference for dealing with reliable established firms. Successful proprietors of firms earned wealth and prestige, with a number of them entering Parliament and gaining other recognition. A problem which they all faced in their ascent was to match the capacity of their firm with workload fluctuations. How to continuously employ the various skills and assets, without slackness or overstraining?

Late nineteenth century New York

Half a century and the Atlantic Ocean separate the second case study from the third. Late nineteenth century New York shared with mid-century London a context of large market (New York population exceeded 1.5m. by 1890) and runaway urban growth. This study draws on Davis (1999) and his concept of building cultures.

While having points in common with London, New York building demand appears to have differed by using capital with greater urgency and dynamism. The industry again was organized on general contracting lines, but grafted on to this were some complicating features. Building owners were likely to begin their projects with more involved funding arrangements. Also, owners commissioned designs from consultants who could belong to sizeable firms in their own right: by early twentieth century some architects' offices were over one hundred people strong. Complexity was further heightened by novel technology (steel frames, lifts, etc.) and tightening building codes. Bids would be negotiated with competing general contractors and an appointment made. Here arose a notable difference from London practice, with wider use of subcontracting. Some subcontracts were initiated by the main contractor for work for which he did not possess the resources. The architects also might arrange subcontracts, probably for high quality or complicated specialist work. More

than in the past, parts of buildings were brought to site ready finished or at least partly prepared: for example, where once bricklayers toiled at hearths and convoluted multi-storey flues, now there were iron heating appliances and pipework. New factory made components and materials included the likes of fireproof partitions, metal skylights and asbestos lagging. This extended the range of suppliers and firms working on site and in doing so added to the general contractors' managerial burdens of co-ordinating, supervising and accounting. General contractors, although carrying overall project responsibility, were becoming reliant on networks of specialist firms.

A difference between New York and London half a century earlier was in technical complexity which complicated management and fostered need for control. While old crafts and informal relations based on trust between firms survived, more businesslike relations with formal, detailed legal agreements were growing. In Davis' words «[s]trong hierarchies of control governed building and general contracting firms . . . » The significant point about division of labour was growth in numbers of different firms. General contractors still held the centre, but specialized firms multiplied all around: an integrated pattern was dissolving into a divided one.

Mid-twentieth century Bristol

The final case study is of Bristol, a representative provincial UK city (1931 population c.400 000) on the eve of the Second World War in 1939. The time was mildly prosperous as a diversified regional economy recovered from recession.

This study draws on Powell's (2002) study of proliferation of firms.

Building demand stemmed from private commerce and industry, and occasional public sector projects. General contracting again prevailed, in another adapted form. As before, building owners often initiated projects with elaborate funding arrangements and then commissioned designs from specialist consultants. There were likely to be at least three specialists (architect, structural engineer and quantity surveyor), reflecting increased technical complexity of buildings and, indeed, division of labour among design functions. Competitive bids were submitted by general contractors and usually the lowest was accepted. Much of the work was subcontracted either by the main contractor or through architects' nomination. Many subcontracts were for supply, or supply and fix, of technically advanced goods: steel frames, patent flooring systems, electrics and so on. Some traditional work such as plastering also might be subcontracted. At least 150 different building-related trades operated in Bristol (as distinct from the total number of building-related firms, which was much larger). About two thirds of the 150 trades were makers: the processors, manufacturers and suppliers of building goods, from plywood manufacturers to metal window makers and others. The remainder, in order of diminishing numbers of trades, may be categorized as: site work trades (engaged in work on site, such as concretors or shopfitters); building services trades (engaged in making or fitting services, such as plumbers or neon sign manufacturers); and merchants (trades engaged in stocking and dealing in materials and components, such as slate merchants or gasfitters' factors). The number of different trades in Bristol had approximately doubled since 1900, with fastest growth among makers and building services. In the half century before 1900 there had also been growth, but it was slower. As would be expected, London, a much larger market, supported many more trades (300 or more in 1900). As the twentieth century had advanced, and transport and communications improved, the London-based specialist trades had increasingly won work in Bristol, where fewer trades were based. Thus, a national building market was beginning to supplant the regional one and, with technical innovation, the number of different trades was multiplying. The result was increasing dependence of Bristol general contractors on whole networks of firms, some based locally and others in London or elsewhere. What was true of Bristol, by implication, was equally true elsewhere in the UK. By 1939 subcontracting had so advanced that general contractors were noted to be mainly concerned with coordinating the work of specialist subcontractors. Specialization had grown so that the number of subcontractors on a project could reach as many as thirty: «[t]he large general contractor of today merely takes on the function of general organizer for the entire project» (Robinson 1939, 15).

Division of labour in UK building had travelled far

by mid-twentieth century. General contractors still occupied a central role, but work on and off site had become yet more intricate, specialized and carried out by specialist firms. It was subcontractors who increasingly performed the physical operations on site, while general contractors were moving far towards being managers, dealing in information rather than directly in goods.

The case studies generally

The case studies do not do full justice to the variety of division of labour. Briefly to emphasize the point are four further UK cases, the first of which is those eighteenth century rural building firms in which were integrated most materials supply and building works on site (Powell 1999). Second are speculative private house developers of the 1920s and 1930s in which were integrated the responsibilities of building owners and builders. A contrast were post-1945 local authority housing providers in which were integrated owners, designers and, sometimes, direct labour site workforce. The only operations not integrated here were materials supply and some minor subcontracted site works. Finally were some postwar industrial «package deal» builders in which were integrated design and building site works (and sometimes site acquisition) (Bowley 1966, 362–95, 419). Such variety renders any evolution in division of labour difficult to trace.

A few simple generalizations can be made about division of labour. One is that a small number of loosely defined functions in the building process were common to all (or nearly all) projects. The functions were those of, first, building owner (also variously referred to in the literature as developer, client, promoter, etc.); second, designers, where appropriate, taken to include architect, engineer, surveyor, etc.; third, suppliers of materials and components; and fourth, makers or builders on site, including installers, assemblers and labour only workforces. Additionally, there were at least two other functions which were more or less significant. They were funding agencies (banks, etc. lending to building owners) and merchants (breaking bulk in materials supply, supplying to site and extending credit to firms on site). Within each function were various trades or specialisms. For example, among the makers might be excavators, carpenters and roofers, while among suppliers might be quarries, timber merchants and paint mixers.

The second generalization is that the number of firms working on a building varied widely from project to project. Each project could be placed on a notional scale stretching from the pole of full integration (one firm did all) to the pole of full division (many firms divided the work between them).

The third generalization is that the functions and the firms referred to above seldom corresponded exactly with one another. Sometimes there was integration: a firm straddled separate functions (and the trades within them). Sometimes there was division: each function, or part of a function, was undertaken by a separate firm. It may be asked, what determined whether there was integration or division?

Explaining division of labour

This section considers some theoretical factors determining firms' choice of function. The factors affected whether a firm undertook an activity for itself (making, not buying from other firms), or transacted in the marketplace (buying, not making). This «make or buy» decision was the key one which, repeated countlessly, determined the extent of division of labour in an industry.

Factors which influenced the «make or buy» decision were of two sorts: those arising from the external context of the project and those within the firm itself. Among the contextual factors, of which there were at least four, was the *extent of the market*. Economist Adam Smith famously pronounced that « . . . the extent of [division of labour] must always be limited by the extent . . . of the market» (Smith [1776] 1954, 1: 15). A large market provided wider opportunities for specialization than did a small market. It followed that advanced division of labour was more likely in London or New York than in a small town. A study (Powell 2002) has noted the relevance of Adam Smith's dictum to late nineteenth century building firms.

The second factor was building owners' attitudes to *risk*. Where they were risk-averse, or where malpractice or failure of firms looked probable, owners resisted using unreliable firms. This could

favour established large integrated firms and thus restrain formation and survival of new small firms. An example of this in action was when small (and notoriously unreliable) single-craft firms were superceded by large general contractors in nineteenth century London. Thus, risk-aversion could favour integration.

The third factor was building owners' *ideology*, rooted in the broad cultural context. Ideology could influence owners' attitudes in favour of one form of division of labour over another. A UK example was mid-twentieth century leftward-inclined local authorities, among them some London boroughs and the city of Sheffield, which at times built by municipal direct labour rather than contracting with privately owned firms (to which they were politically antipathetic). In this example ideology favoured integration; elsewhere with different ideology, the reverse might be the case. Ideology in this sense appears as a wild card, not readily classified or susceptible to generalization.

The fourth factor was *workload fluctuations*. These were (and remain) endemic in the rather volatile construction industry, and were often central to the survival (or death) of firms. A firm faced with growing demand had to decide whether to expand capacity or to subcontract. In the opposite case of a firm faced with falling demand it had to decide whether to retrench or to retain costly unused capacity in the hope of an upturn in workload. Firms which subcontracted in busy times had the effect of increasing division of labour in the industry; those instead remaining integrated could face difficulties in times of recession. Thus, fluctuations and business strategies to cope with them favoured division of labour.

Four more factors influencing firms' «make or buy» decision remain, all of them internal to the firm. The first was the *availability of capital* or credit, and the entrepreneurial spirit to make use of it. Where these were scarce, small firms in a divided industry would have been deterred from growth and, possibly, integration. Thus, scarcity of capital would have favoured low division of labour, as among the Florentine wallers. Also connected with availability of capital was ease of entry of new firms. Where there was little need for capital, firms could easily begin trading and could readily proliferate (as did, say, painters). On the other hand where new firms needed much capital, there were few small firms. A case was cement producing firms, few and large because they needed costly plant. This leads to the next factor.

The second factor was *ease of integration of technology* in making buildings or their parts. Some technologies were inherently easy to combine and others less so. For example, a nineteenth century brickmaker might easily enough set up also as a tilemaker: raw materials were similar and so were kiln firing processes. The ready technological possibility of combining brickmaking and tilemaking encouraged integrated firms. An example of the opposite case was brickmaking and joinery manufacture. Here, neither raw materials, manufacturing processes or labour skills were held in common, so integration offered few advantages. Often integration was affected by the potential for economies or diseconomies of scale. For example, producers of structural steelwork benefited from economies of scale and this favoured integrated firms. On the other hand, where economies of scale were few, such as among jobbing builders, integration was far less common.

The third factor was *transaction costs*, the costs to firms of trading with other firms, which arose with a decision to buy rather than make. Transaction costs were incurred when firms searched where to buy, specified what was wanted, negotiated, monitored and enforced contracts, and the like. Where transactions were enacted frequently, costs often diminished (Gruneberg and Ive 2000, 123–4). Some building cultures had inherently higher transaction costs than others. What made the difference were prevailing levels of trust and business probity, ease of communications and existence of standard documentation and procedures. A comparison which illustrates this comes from late eighteenth century UK rural builders. Their transaction costs, with slow communications, probably were higher than those in, say, late nineteenth century New York where communications were far more developed. Thus, high transaction costs favoured integration.

The final factor was *technical innovation*. When innovations occurred, new firms were often set up to trade in them. For example, the advent of novel structural frame systems, fireproof floors and partitions, electrical services, precast concrete, and so on, led to new engineering-based firms. Older building firms, steeped in craft traditions and

sceptical of change, often preferred to stay with what they knew and to leave novelty and attendant risk to others. Thus, technical innovation encouraged new specialist firms and high division of labour. The point is illustrated by comparison between London firms in c.1850 and 1900 which shows very many new firms entering the market with innovative products, such as patent glazing contractors and electrical goods suppliers.

The probable influence of these factors on division of labour is summarized as follows. Seldom was any one single factor necessary, or sufficient, to give rise to a particular pattern of division of labour: the factors worked in combination. High division of labour (many firms) was more likely where one or more of the following predominated:

— large market
— low risk aversion among building owners
— favourable ideology
— widely fluctuating workloads
— readily available capital
— building technology unsuited to integration
— low transaction costs
— many technical innovations.

On the other hand, low division of labour (few firms) was more likely where one or more of the following predominated:

— small market
— high risk aversion among building owners
— favourable ideology
— stable workloads
— scarce capital
— building technology suited to integration
— high transaction costs
— few technical innovations.

Further case studies from a wider range of building cultures might add to the list of factors. Moreover, further work probably would enable the factors to be given priorities, distinguishing major influences from minor. Would causes of division of labour emerge more clearly relative to period, place, level of technology and so on?

Significance of division of labour

What of significance to construction history emerges from this somewhat abstract study? Eight factors have been introduced which appear to determine the extent of division of labour between firms in construction. Arguably, the factors offer some insight, at least, into who did what in building and all that this implied: the distribution of power, the roles and responsibilities, and priorities which prevailed on projects and their contexts. Industrial organization and division of labour deserve to be more widely recognised as playing a part, just like climate, gravity, user needs and so on, in shaping the forms of buildings.

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Evolution of the analysis criteria for wooden arch structures between the 16th and the 19th century

Enrico Quagliarini
Alessandro Stazi
Marco D'Orazio

We report the results of a research that has faced the study of the historical development of the analysis methods for arch wooden structures between the XVI and XIX the century. The research demonstrates that at the end of the XVI and during all the XVII century, the experiences of Galileo and Mariotte on the resistance of wooden beams turn out to be a prerogative of a narrow number of academics. It is only during 1700 that the scientific results of the previous centuries find practical applications and they start to be gradually introduced in several fields of structural engineering. Until that moment, all wooden structures are based on design criteria directly derived by the experience of the carpenter consolidated during time.

In the first half of 1700, engineers begin to be more interested in the problem thanks to the numerous experimental researches on the «force» and on the «elasticity» of the lumber. But at the beginning of 1800, the first studies that regard the analysis and verification criteria of the arch wooden structures appear, even if they are still approximate. One of the first person facing the static problem of curved wooden pieces is Duleau, and the same Navier introduces some interesting methods of analysis for the determination of the thrust of the wooden arches against their supports.

J. A. C. Bresse gives one of the first systematic and rigorous, from a methodological point of view, essay of such issue. He writes a book entitled «Recherches analytiques sur la flexion et la resistance the des pieces courbes» where he supplies not only an analytical deepening, but above all he encloses a useful working instrument for all the engineers of that time for the calculation of the thrust of such structures through suitable tables.

The experiences of excellent authors of the past become an important part inside of this historical frame. Thanks to their constructors and designers experiences, they try to process dimensioning methods for wooden arch. We introduce in particular the studies carry out by Rondelet, by Emy and by Curioni.

Wooden arches in 16th and 19th century treatises

This paper shows some of the results of a study of wooden arch structures as concerns both their historical evolution and the relevant dimensioning and control criteria.

The treatises we have considered show that the knowledge related to these structures was first written down around 1500 and was mostly widespread around 1800. 16th century French manuals were the first to exhaustively describe the manufacture of arch structures by means of wood carpentry techniques. In particular towards the middle of the 16th century, French builder P. Delorme (1561) described in his

well-known treatise[i] an innovative system for building wooden arch roofs based on the use of centrings made up of boards cut into the shape of an arch, put close to one another and arranged in vertical planes through staggered joints, then clamped by means of wooden dowels and connected by means of transversal through rafters.[2]

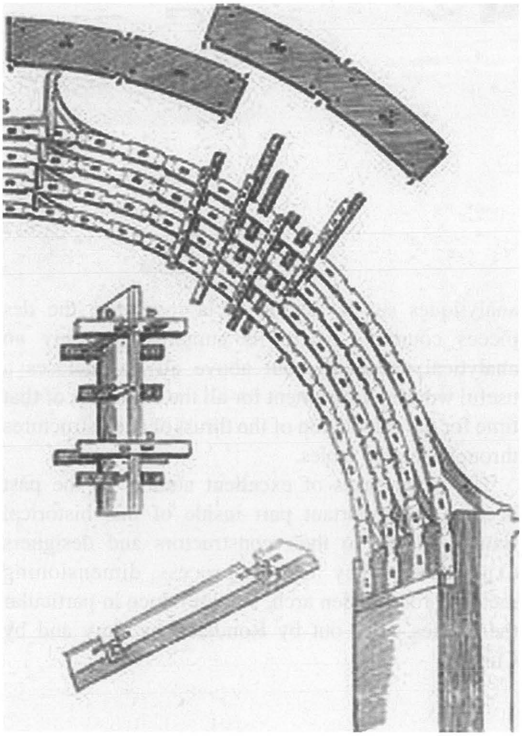

Figure 1
Delorme's system

Except for Delorme, the other manuals from that period describe the connections of the wooden centrings in more general terms and the authors only rarely go into further detail as regards building techniques.[3] Moreover, as Emy says:

> Filiberto de Lorme's beautiful discovery . . . was completely forgotten for two centuries. After the death of this well-know architect no falsework was made according to his system and it was not until a few years after Legrand and Molino (1767) applied it to the corn market dome in Paris that this construction technique became popular (Emy, 1862).

It is probable that it was up to architects and carpenters to decide on the techniques to be used — according to their own ability. That is why they devised personal and peculiar solutions that best suited the situations they were to cope with. As a mater of fact, the sizes to be covered would vary from two or three meters to twenty meters, which caused them to think up solutions specific for each structure.

It was only in 1825 —after almost three centuries, that Colonel Emy put forward an original solution for the construction of the centring structure in the roofing of a large military location situated in Marac. It consisted in arranging the boards flatwise the one on the other, bending them conveniently as work was carried on and taking advantage of wood's flexibility

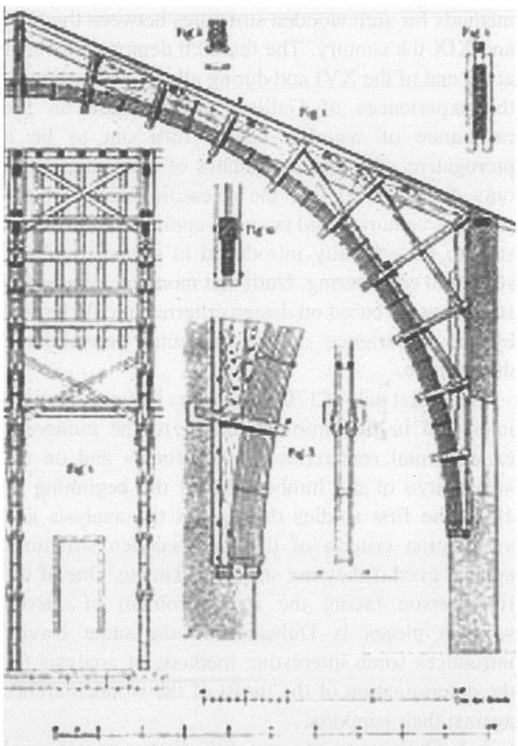

Figure 2
Emy's system

—maintained by bolts and bindings, as a carriage's springs. This system proved to be very suitable whenever large-sized wood was available, its simple joints needing less specialised labour than Delorme's system. Delorme's system was to be preferred either for small spaces or whenever small wooden boards were available.

It seems now convenient to have a look at general calculation methods for wood and the relevant historical development in order to have a better idea of the issue under consideration. After that, some of the dimensioning criteria applied in the course of time to wooden arches will be considered directly.

DIMENSIONING CRITERIA APPLIED TO WOODEN STRUCTURES FROM THE 16^{TH} CENTURY TO THE 19^{TH} CENTURY

During the 15^{th} century the innovations from the school of Paris and the school of Oxford began to spread, although Aristotelian tradition remained well-rooted. Particularly interesting are the research and experiences related to the resistance of materials that make it possible to consider Leonardo da Vinci «as the wise founder of construction theory as it is today, as well as the brilliant forerunner of Galileo» (Parvopassu 1953).

But it was not until Galileo in the early 16^{th} century that the laws of mechanics were applied to the resistance of solids in general and wood in particular by studying them as made up of fibres that behaved differently according to the direction in which the load was applied. Galileo assumed that «resistance» at the moment of breaking was evenly distributed on section AB, Figure 3b. In fact, if we suppose that the elastic material is linear and the section is rectangular, the distribution of tension is as shown in Figure 3c. For a material of this kind Galileo's theory gave a value three times larger that the breaking value.[4]

After Galileo, Mariotte (1620–1684) dealt with resistance to bending in wooden beams. His experiments showed that Galileo's theory had given exaggerated values for ultimate tensile stress. So he devised his own theory taking into consideration the elastic properties of the material, after noting that elongations were proportional to the forces applied. In this case, the distribution of tension was correct —always assuming the material to be linearly elastic— but the moment of resistance of the section was not.[5]

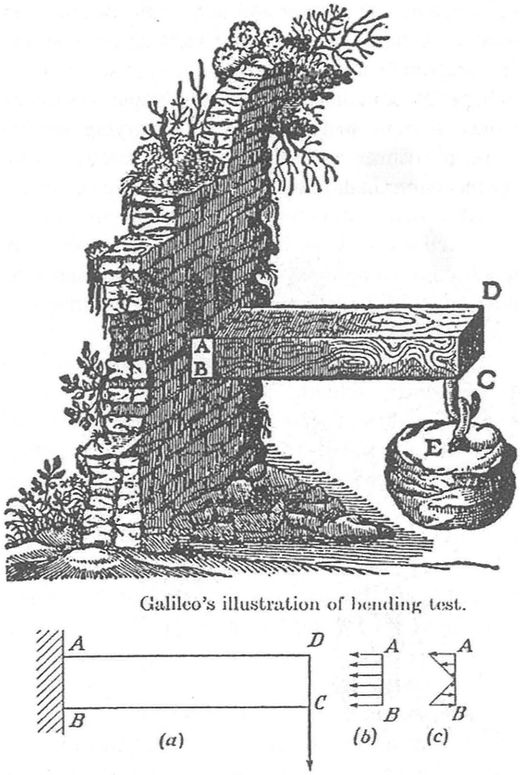

Figure 3
Bending test by Galileo and reference diagrams

During the 16^{th} century, few people were interested in the mechanics of elastic bodies and its consequences on practical issues. So only fey scholars dealt with the issue, out of mere scientific curiosity. It was only in the 18^{th} century that the scientific results obtained in the previous centuries could be put to practical use and began being introduced in several engineering sectors.[6] The developments in the field of military and structural engineering required not only wide experience but also the ability to cope with the new problems in a rational way. It was this century that saw the inauguration of the first engineering school and the appearance of the first structural engineering books.

In 1713 Parent *(Essais et Recherches de Mathematique et de Physique)* corrected Galileo's and Mariotte's mistakes on the moment of resistance

in a rectangular section and dealt with the issue of how to obtain the maximum rectangular resistant section from a circular frustum.

In 1729 Belidor applied Galileo's and Mariotte's work to the experiments he was carrying out on wooden beams, eventually obtaining practical rules for the determination of the minimum size of beams. Besides that, after having seen that in general constructions such as bridge trusses or roofs were much more complex systems than simple beams, he devised an investigation method useful to dimension each framework.

Musschenbroek's important contribution was subsequently added. In his work «Physicae experimentales et geometricae» (1729) he tested small samples and described methods to test materials such as wood that could be as resistant as much larger pieces. He was also the first to experimentally investigate the instability of compressed columns, finding out that the limit twisting load was inversely proportional to the square of the length of the column. The only limit for this research was that the woods were supposed to be defectless —which is not the case in reality.

An important leap forward in the study of forces in wood was made by Buffon (1775). His research showed that the resistance of wooden samples taken from the same trunk varied considerably according to the position they had been taken from. Because of that Buffon criticised Musschenbroek's use of small samples and used larger samples in his own experiments.

In the wake of Buffon's work, Lomblardie first (1747–1797) and Girard after him in the last decades of the 17th century focused their attention on the elasticity of wood and its maximum camber. Girard, the author of the first book on the resistance of materials, built a special equipment. The experiments he carried out showed not only that wood is a material far from being perfectly elastic but also that deformation increased in time under a certain load.

Further contributions came from scholars such as Barlow[7] (1776–1862) in England and Dupin[8] (1784–1873) in France, bringing about new knowledge on woods and their resistance —with or without elasticity alterations.

In the early 18th century there were formulas allowing for the calculation of the resistance of wood, although they referred to single isolated pieces, while what was especially interesting in practical terms was the behaviour of the piece inside a structure. That is particularly the case with arch structures such as Delorme's and Emy's:

> a piece of wood that is naturally or artificially bent, and is soundly supported at its ends, is subjected by a given weight to only one third of the bending it would be subjected to if it were straightened and freely resting on two supports. (Sganzin, 1832).

Duleau (circa 1820) was one of the first scholars to cope with the static problem of bent wooden pieces. He saw that if the load was in the middle, the half third of the arch bended under thrice the weight that would be produced by the natural or artificial primitive camber. And if the weight was applied to one fourth of the opening, half the arch bended under twice said weight. He also noted that in Delorme's and Emy's centred falsework systems, the sides were always reinforced by linking pieces with horizontal inclined parts ending the falsework at the extrados and were stronger in the middle so that the resistance and stiffness required were simultaneously obtained in this way.

In 1831 Navier[9] (1785–1836) introduced in the Annals of bridges and roads a few interesting calculation systems for the thrusts of wooden arches against their supports. In the very same period Bresse (1822–1883) gave his greatest contribution to construction theory thanks to his theory on bent beams and its application to the designing of arches. Not only did he give a general solution to the problem, but he also presented a detailed series of solutions to specific cases so as to supply engineers with a useful work tool.

In those years some well-known builders —more or less influenced by the period's theoretical and analytical discussions— used their experience to work out dimensioning methods for wooden arches that could be useful in their work. Among them Rondelet, Emy and Curioni should be remembered.

The calculation of wooden arches

What has been said so far shows clearly that until the 19th century the culture of construction was somewhat lagging behind scientific culture. Such discrepancy

can easily be appreciated if the experience of three 18th century authors are reported that —although limited to one century— show the various stages of evolution of the analysis criteria used for wooden arch structures before today's theoretical approach. The initial «geometrical stage» based on «proportional dimensioning» (Rondelet) led to a «reductionist stage» based on the reduction of the arch to an equivalent beam (Emy) where the framework was already tested through resistance formulas, eventually leading to the «elastic-linear stage» (Curioni) based a geometrical-differential approach of the first order where the first two «coefficients of elasticity» (longitudinal and transversal) were presented to allow for the different behaviours of the bending-stressed or shearing-stressed material.

The calculation of wooden arches according to Rondelet

Rondelet (1734–1829) believed that for wood dimensioning it was necessary to bear in mind that this material had an absolute force and a relative force. The former was given by the stress needed to break a piece of wood by pushing it at its ends according to the direction of its fibres. The latter depended on its position. Rondelet performed numerous tests to obtain the forces of various woods that he properly tabulated into a remarkable variety of sizes and proportions. These tables enabled designers to know the force —both absolute and relative— that wood could bear —with a reduction to one tenth of the value found to have a safety margin— regardless of the wood being vertical, horizontal or inclined.

In his treatise Art de Batir (1802) showed several applications for wood calculation, while there was no actual example of arch dimensioning —although these structures were already well known at the time. The author points out the calculation of the supporting centrings as a reference (illustrated later in this text).[10]

On the assumption that our structure is as shown in Figure 4, Rondelet suggests carrying out the following operations in order to find a combination of woods resistant to the stresses from the corbels:

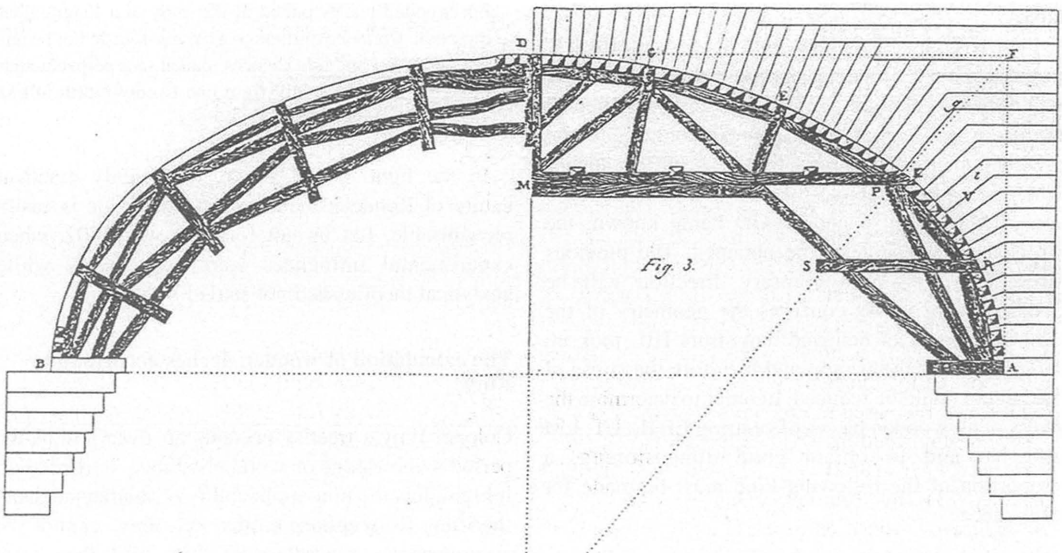

Figure 4
Rondelet's centring for dimensioning

- first of all determine point F given by the intersection of the tangent to point A and point D. For F draw the perpendicular to the curve that is to intersect it in point K (the point determining the position of the anchor);
- divide part KD in 2 o 3 sections according to the length. Draw other perpendiculars to the curve from points E and G to determine the positions of the two intermediate posts;
- from point I draw line HIL to indicate the position below a strut to support the anchor and above it that of a strut to counterthrust the upper part of the post GT, as supported on the other side by strut LM that exercises force with the middle post;
- divide the lower part of the anchor in 2, 3 or 4 sections for the passage of brace-laths RS.

The stress **s** produced by the anchor on the arch RK over 30° (until then the ashlars of the masonry do not need any support as they are self-bearing) indicated by the letters RigK «must be to the weight as the horizontal iK is to the arch KR».[11] The weight P and iK/KR being known, a simple proportion is enough to obtain the stress required. The stress and the resistance of the material being known, the area of the section of the anchor can be easily derived from the tables.

In order to evaluate the weight of the vault from K to the keystone, Rondelet observed that the centring will need to bear about 2/3 of it. The load will then be borne on the anchor with a stress contrary to the previous stress. To derive the stress on the anchor KM, the same principle as seen before is applied: s: p = KM: KEGD. p and KEGD being known, the stress on the anchor can be obtained. The previous stress exercised in a contrary direction will be deduced from it. As concerns the geometry of the centring, Rondelet believed that struts HIL took on more than half the weight and therefore the stress of the anchor could be reduced. In order to determine the stress of all wooden pieces of centring EI, IL, LT, LM and No and to obtain good dimensioning, a proportion of the following kind must be made for each piece:

> total sine is to the sine of the inclination of the joint on which it rests as its weight is to the force required to support it —acting in parallel with the joint— that is the one opposed by the centring. Indicating total sine with St, the sine of the inclination of the joint with Sn, the weight of the corbel with P, and the force required to sustain it with F, we will have St: Sn = P: F, hence F = (Sn × P)/St. That is to say the weight of each corbel must be multiplied by the sine of the corner of the joint on which it rests and the product divided by the total sine (Rondelet 1831).

Besides that Rondelet —to have a safety margin— recommends that joints be well built. Otherwise the simple dimensioning of the single pieces will not be enough. As a matter of fact:

> it is essential to know that it is not enough for each piece to have sufficient force to resist partial stresses corresponding to the points where they are situated. Also, their connection need to be sound and stable enough to resist the mass of all the stresses together and moving, in consideration of the defects and imperfections of the wood, their connection and laying, as well as extraordinary loads and accidents the centring may be subject to. Therefore I believe that the sizes of the wooden pieces making up the centrings may be determined by means of the method used for all wooden works that are to bear remarkable loads or stresses. This rule consists in giving the pieces that are to resist the stresses compressing them at the ends in a longitudinal direction, from one twelfth to one tenth of their length. For wooden pieces pulled at the ends in a longitudinal direction, from one thirtieth to a twenty-fourth. For beams of every kind and other pieces loaded in a perpendicular direction to their length, from one twenty-fourth to one eighteenth (Rondelet, 1831).

In the light of the above, the mainly practical nature of Rondelet's approach to the issue is easily recognisable. Let us not forget it was 1802, when experimental influences were very lively while analytical theories had not settled in yet.

The calculation of wooden arches according to Emy

Colonel Emy's treatise presents an overview of the period's knowledge on wood resistance. In particular, it highlights the non-applicability of mathematicians' theories to wooden solids, as they cannot be homogeneous, regardless of how well they were built.[12] Construction theory —according to the author— should have adopted a simple calculation method rather than a complicated strict one —the

latter being more difficult to be applied and its results only slightly more reliable.

Starting from Galileo's formula, the simplest resistance formula known at the time (although it was not true except for a few particular cases):

$$R = \frac{feh^2}{l}$$

where *e* is horizontal thickness, *h* is vertical thickness, *l* is length, *f* is a coefficient dependent on the wood's force, and *R* is the resistance of the piece of wood, Emy chose to rely on the experiments carried out by Buffon rather than Rondelet's. To this end he supplied two tables: one showed the results of experiments with pieces of oak in terms of *camber of the bending at the moment of breaking,* the other showed the ratios between the forces of the different species of lumber so that one could derive the resistance specific to the wood they were interested in (Figure 5).

In coping with the problem of bent wooden pieces, Emy maintained that, if straight pieces were compared to bent pieces, naturally bent pieces proved to be much more resistant than pieces bent by means of an adze. In this regard he stressed that experience was not enough to work out a theory on bent pieces: «I believe I am the first to highlight that round arches and even more so compressed elliptical arches used in trusses of roofing —as well as in flexible elements— exercise a thrust in the plane where the points normally drawn in masonry vaults are with the name of "reins"» (Emy 1862). The following experiments demonstrated the existence of this thrust due to the flexibility of an arch that cannot keep its circular shape (Captain Ardant's experiment). This thrust was suitably opposed by the author, who added planks to the thickness of the arch in order to increase local stiffness.[13]

For framework dimensioning Emy makes reference to an approximate calculation to be applied to *bent madrieri in the direction of the length*: the arch is divided in three different parts by means of the two points where it joins the struts (Figure 6). Based on the increased stiffness of the reins and in correspondence with the thrust, the stiffness of the arch —or alternatively its resistance— is reduced to that of a piece dd' established on each part, «as a

INDICAZIONE dei legnami	RESISTENZE		
	allo schiacciamento	allo strappamento	allo spezzamento
1. Quercia.	807	1881	1000
2. Olmo	1075	1980	1077
3. Faggio	1112	1800	1072
4. Abete	850	1250	918
5. Tiglio.	717	1406	750
6. Pioppo cipressino . .	717	1293	624
7. Pioppo.	680	940	586

Figure 5
Buffon's lumber conversion table

support would be whose fibres were tangent to the fibres of the arch in the point where they meet the less resistant plane with the line rs as a trace» (Emy 1862). The straight piece is supposed to resist compression as the arch in the direction of its fibres under the pressure exercised by the weight of the roof and its covering as well as bending, which might be produced by the weight of the roof and its covering —acting along the vertical mo made up of two forces.

Hence, P being the weight of the roof pitch —including the weight of the covering— and Q being the stress produced in the direction of the fibres of piece dd', and a being the angle that piece dd' created with the vertical, we have for resistance to compression:[14]

$$Q = \frac{P}{\cos a}$$

With reference to resistance S of the material, the required area A is obtained ($A = Q/S$). In this way the part of the arch considered as straight can be dimensioned.

If I take R (the component along mq) I see that $R = P \times \text{sen}a$ and if I consider the force in or according to what has been shown, I see that the two forces applied to the ends of the weight dd' correspond to one single double force applied to point r in the direction or being in d and d'i (two supports). So I obtain $R = 2P \times \text{sen}a$. Now, if I check the stress based on previous Galileo's formula, it must be stated that the last value is higher than the previous value to have a safety margin, neglecting any reinforcement contributions from the arch structure.

While carrying out these studies on dimensioning, Emy anyway invited builders to always put experiments before any construction activities, as they should only be a verification of what has been calculated.

The calculation of wooden arches according to Curioni

Curioni coped with the calculation of bent wooden building elements in further detail than his predecessors. The presentation is of practical nature

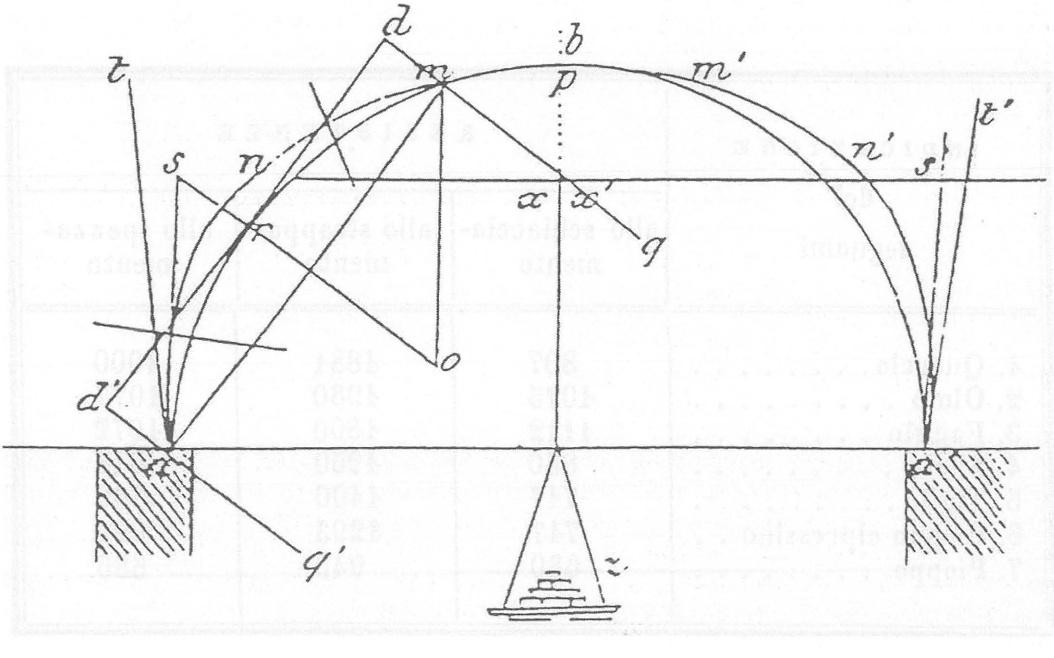

Figure 6
Emy's approximate calculation

in order to meet the builders' requirements, without neglecting the recent analytical approach to the issue.[15]

The calculation of a wooden arch is dealt with based on several hypotheses. In particular, the author refers to one for the centrings of roofings, i.e. structures whose directrix «is meant to be half the circumference of a circle, a circle arch, a pointed arch, and sometimes even a parabolic arch or an elliptical arch. Their ends are either fixed to supports or can take on slight movement. Sometimes they are subtended by tie rods destined to neutralise the effects of their horizontal thrust; or there may not be tie rods and the piers are given such dimensions as to be able to resist both the pressure they are subject to and horizontal thrusts» (Curioni, 1864).

In order to approximately determine the right section of a centring Curioni makes reference to the iteractive method illustrated in his «Cours de mecanique appliquee aux constructions» by Engineer Collignon.

Ω is assumed to be the constant surface of the section of the arch (Figure 7) and Φ is assumed to be the angle BOD. Q and V are the horizontal and vertical reactions exercised by the support on the section of springer AB. Let us consider the normal in E of section AB and the angles NEQ and NEV respectively Φ and 90-Φ. Pressure in section AB on the surface unit is expressed by (1):

$$\frac{Q \times \cos \Phi + V \times \mathrm{sen}\ \Phi}{\Omega}$$

With reference to the theory presented in his treatise on the resistance of initially bent solids «maximum pressure as referred to the surface unit in a section whatsoever of an initially bent solid results from the algebraic addition of two terms of the form $\nu\mu/I$ and T/Ω, where letters Ω and I represent respectively the surface of the right section in question and the moment of inertia of said section with respect to the parallel to the neutral axis as drawn through its surface centre; T and μ represent the compressing tangential force and the bending moment for the right section indicated; ν represents the distance of the fibre most compressed by said parallel to the neutral axis. The influence of the $\nu\mu/I$ term may be reduced as much as possible by conveniently adjusting the shape and the section and

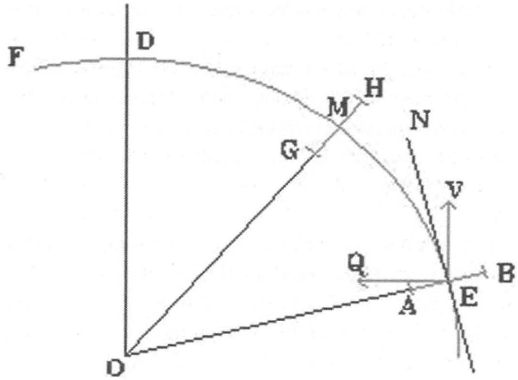

Figure 7
Curioni's scheme of calculation

leaving surface Ω unaltered. We can therefore admit —at least provisionally— that the centring will be in good stability conditions by causing the average pressure given by expression (1) to be a given fraction (e.g. 2/3) of pressure n″ R″ that can be borne by the material making up the centring itself. The following equation can thus be established (2):

$$\tfrac{2}{3} n'' R'' = \frac{Q \times \cos \Phi + V \times \mathrm{sen}\ \Phi}{\Omega}$$

where R″ is the breaking coefficient under pressure and n″ is the relevant stability coefficient» (Curioni 1864)[16].

At this point, in order to obtain Ω, we need to derive Q and V. As concerns Q, it can be derived from the following formula (3):

$$Q = \frac{p \times c^2}{2m}$$

which is valid for a balanced arch with a span 2c and a rise m, respectively equal to the span and the rise of the arch for which we wish to find value Ω —loaded with a weight p for each unit of length of the span.

As concerns V, it can be derived from the sum of several contributions:

1. the weight of half an arch equal to $\Pi S \Omega$, where S is half the arch development and Π is the

weight of the volume unit of the material it is made of;

2. the weight of all that the half centring is to bear permanently such as purlins, boarding or lath, covering and connecting pieces;
3. the weight of maximum overload on the covering.

If U represents the sum of contributions 2 and 3, we derive for V the formula (4):

$$V = \Pi S \Omega + U = p \times c$$

and we can arrive at the following equation (5):

$$\tfrac{2}{3} n'' R'' = (\Pi \times S \times \Omega + U) \times \frac{c \times \cos \Phi + 2\, m \times \operatorname{sen} \Phi}{2\, m \times \Omega}$$

from which the expression of Ω can be derived that is useful to provisionally determine the right section Ω of an arch and therefore its overall weight, when Ω is multiplied by the product $2S\Pi$. Formula (6) is then derived:

$$\Omega = U \times \frac{\dfrac{c \times \cos \Phi + 2\, m \times \operatorname{sen} \Phi}{2\, m}}{\tfrac{2}{3} n'' R'' - \Pi \times S \times \dfrac{c \times \cos \Phi + 2\, m \times \operatorname{sen} \Phi}{2\, m}}$$

The section and weight of the arch having been determined, we can now calculate the dimensioning of the arch in the case of a circular arch with fixed ends.

The weight of the covering and fortuitous loads is transferred to the centrings through the purlins. That is why we can consider the various arches as solids loaded with a weight uniformly distributed on their curvilinear axes. The weight must be expressed in kgs and be referred to the length of 1 metre. Once V has been found, V/S can be derived and then the weight $q = V/S$ can be obtained with reference to the unit of length of the axis of the centring in question.

Let us take the geometry of the arch to be studied and let us consider r as the radius OD of the axis EDF of the centring (see previous Figure), Φ as the arch with a radius equal to the unit closing the angle EOD and Q as the horizontal reaction of the support against the section of the springer AB. The value of Q may be determined by using the results of «Problems on the deformation of constant cross section arches with the axes arranged on vertical planes and loaded with weights» (Curioni 1864).

The following can thus be derived:

$$Q = q \times r \times \frac{9\Phi - 10\Phi \times \operatorname{sen}^2\Phi + 4\Phi^2 \times \operatorname{sen}\Phi \times \cos\Phi - \\ -9 \operatorname{sen}\Phi \times \cos\Phi}{-2\Phi - 4\Phi \times \cos^2\Phi + 6 \operatorname{sen}\Phi \times \cos\Phi}$$

Now, if φ is the angle MOD determining a right section whatsoever GMH of the centring and m is the bending moment of section GMH of the centring, we obtain:

$$\mu = q \times r^2 \times (\varphi \times \operatorname{sen}\varphi - \Phi \times \operatorname{sen}\Phi) + r \times (q \times r + Q) \times \\ \times (\cos\varphi - \cos\Phi)$$

Now it is possible to see the value of tension T (normal) and shearing stress N in any section of the arch.

As a matter of fact, if I take my arch and evaluate the component of the forces Q and V —knowing that $V = q \times r \times \varphi$—I obtain:

$$T = -(q \times r \times \operatorname{sen}\varphi + Q \times \cos\varphi)$$

$$N = q \times r \times \varphi \times \cos\varphi - Q \times \operatorname{sen}\varphi$$

At this time, we can estimate the safety margin we have obtained, confronting the maximum values of the sollicitations with the respective *equations of stabilities*, relative to the normal effort and the cross-sectional sliding.

Conclusions

From this paper it clearly emerges as until the 19th century the arch wooden structures dimensioning is first of all based on the constructor's experience and on his direct experiences handed on during time rather than an analytics appraisals: every structure demanded specific sagacities that most of all were resolved directly in yard, the only numerical control, if carried out, was entrusted to simple rules of proportions between the parts.

Such approach is not completely exceedeed during all the 19th century: every constuctor has a different approach to determine the sollecitations acting on such structures, even if during such period

this problem had a well defined heoretical formulation thanks to the works of Navier and Bresse. Anyway, the necessity to confront the obtained sollicitations with more or less empiricists formulas of resistance, reduced by opportune coefficients, is well known.

After all, knowing the scientific instruments and the numerical approaches of the past and the constructive recommendations during the several ages is sure a right step to design a correct intervention of recovery on whichever type of structure.

Pick the structure with the eyes of its own time, in fact, allows to comprise because of *that* structure, evidencing some of its virtues and defects by the light of our present acquaintance.

NOTES

1. In 1561 Delorme published «Nuove invenzioni per costruire bene» on how to build arched surface roofs made up of boards connected to one another. He is considered to be its author, although this technique was certainly older, as it was used in building the domes of the San Marco cathedral in Venice in the 11th century (Serlio 1584). The hemispherical upper half of the domes —which were renovated by Sansovino in 1530— are made up of boards joined in two laid on edge exactly according to the method that was to be named Delorme's system. Anyway, he was the first to apply this method to two-slope roofs and to think of connecting these bends to the links crossing them, fastening them in order to contain them and make them more resistant.
2. The idea at the basis of Delorme's philosophy can be clearly explained by Franco Laner's words (1994): « . . . the vault is built in the same way as a wall, i.e. by summing up several basic elements, which are bricks for the wall . . . ». But, the vault being much more complex than the wall, it needs a much stronger building concept behind it. The reduction of the vault to small pieces is not the consequence of the lack of large elements —as some authors seem to believe— but is a «recourse to rationality» (Laner, 1994) finally resulting in the reduction to the piece that is the simplest and the easiest to be repeated and made.
3. In Italy written information on building techniques appeared in the manuals dating from the 16th and 17th centuries (Scamozzi 1615; Milizia 1715; De Conti di Cleppio 1784). At the same time such techniques were widely used in churches and palaces thanks to the possibility of making enormously complex vault geometries.
4. In fact, materials do not remain linearly elastic until they break. So the distribution of tension is different from that shown in Figure 1c and decreases the difference between the value foreseen by Galileo and actual breaking value.
5. See Timoshenko, «History of strength of materials», pages 21–24, 1953.
6. It was in the 18th century that the role of the engineer as «the bearer of the scientific and technical culture inspired by Enlightenment» began to emerge more clearly. In was also in this century that the tabulation of the experimental results useful to the dimensioning of the structures became as widespread and reliable as never before» (Benvenuto, 1981).
7. Barlow published in 1817 a book entitled «An Essay on the Strength and Stress of Timber». The book became very popular in England and was printed several times, especially thanks to its practical nature.
8. Dupin carried out important experiments on inflected wooden beams. He used different kinds of wood in order to show that their resistance increased as their specific weight went up. He also saw that deformation is proportional to the load in a wooden beam simply resting on a surface up to a certain limit, while it increases faster beyond said limit.
9. Navier contributed greatly to the theory of inflected beams by calculating analytically the thrust of parabolic and circular arches under varying load conditions.
10. In calculating the centrings, Rondelet opened the way to the calculation of bent wooden elements, in consideration of the centring having a different structure from that of the wooden arch, as it is made up of several parts —it is a network structure.
11. See the theory explained by the author in Chapter I, Section 4 of the Ninth Book (Curioni, 1864).
12. Emy also believed that a piece of wood was to bear one fifth or at the most one fourth of the weight causing it to break. The reduction in the load was to be carried out based on constraint, geometry and load modes.
13. In Delorme's system this thrust and the relevant sagging are seen. But they cannot be removed by adding material. This is due to the different construction system that gives more importance to flexibility of board joints that that of the boards themselves —the latter being limited by the small size. That is why this is very similar to what happens in freestone vaults, where the boards are joined and *laid on edge just like wedges*. The only solution to this problem comes directly from stone vaults, where springer thickness is increased.
14. Such formula does not represent the axial stress that we commonly consider and that should be $Q = P \times \cos a$ from figure 6, but it is just a compressive external load

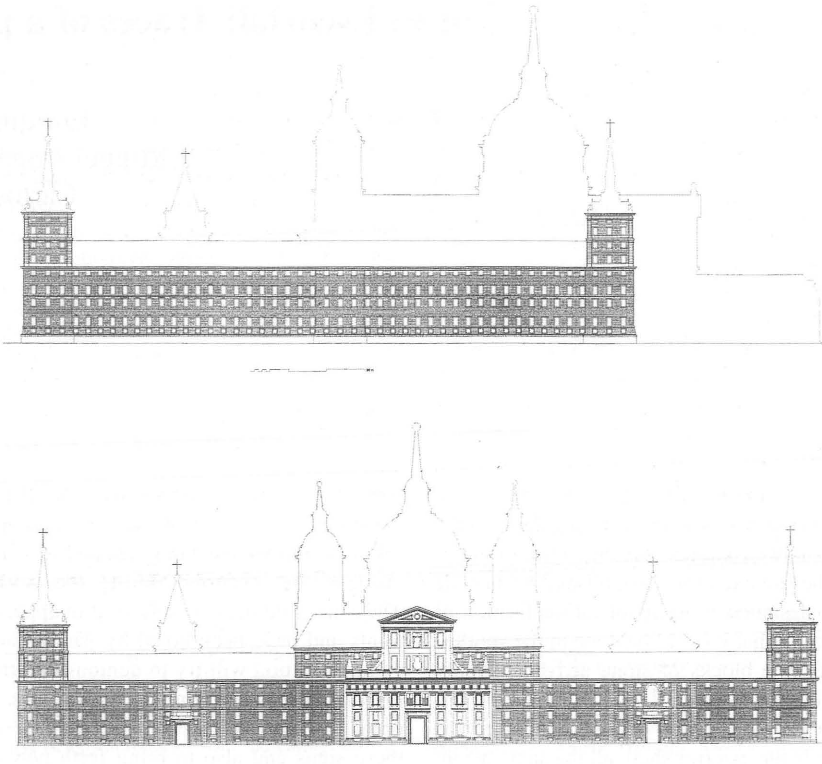

Figure 1
From top to bottom, the elevation work done on the south, west and north facades and the original distribution of the spaces and pilasters in the north façade

with four bearing points whose coordinates were obtained by laser. The drawings thus obtained were revised in situ, in order to eliminate possible errors or omissions.

The data, well known by all, are the following. During the construction, there was a change of management from Juan Bautista de Toledo to Juan de Herrera, and also a change in the plans. The original division in four posterior floors and two anterior ones was changed to a uniform height of four floors, in addition to the corresponding increase of the anterior bays, which can be seen in the front towers, whose floor plan is L-shaped. In the main façade, there are signs of two pilasters, which were removed. In the north façade, there is evidence of a more important change in the distribution of the pilasters and secondary openings, made by Juan de Villanueva (Sambricio 1988; Ortega 2000) (Fig. 2). On the south facade, which has no pilasters, one can see the signs of the middle tower that was removed, the horizontal separation between spaces is slightly different from one side to the other and many irregularities in the position of the ashlars is visible.

Once the relief of the pilasters was eliminated, in order to erase the marks, the constructors had recourse to diverse tricks of the trade. False joints were used, that is, joints worked over the stones and re-joined with a superficial braid of mortar (which has frequently fallen off). They also tried to dissimulate the presence of real joints, regrouping them with a special mortar of granite sand that looked like stone. When the lines of the elevation were registered, in addition to these two situations, it was necessary to add the lines that separate two parts of a same stone with different relieves, as occurs in the teethed stones of the pilasters or in the windowsills. (Fig. 3).

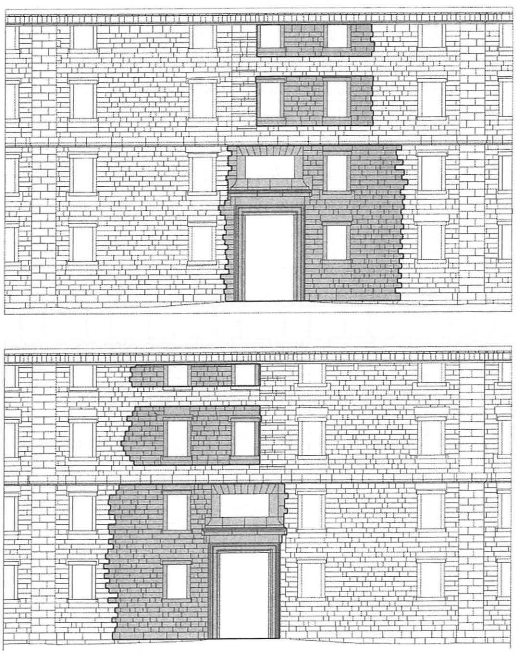

Figure 2
Area in which the ashlars are new or are displaced from their original position

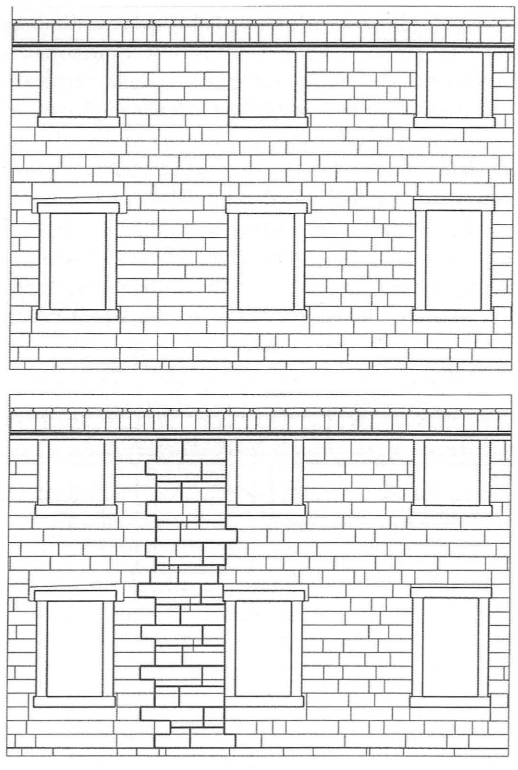

Figure 3
Apparent joints and actual quartering in the space where a pilaster was eliminated

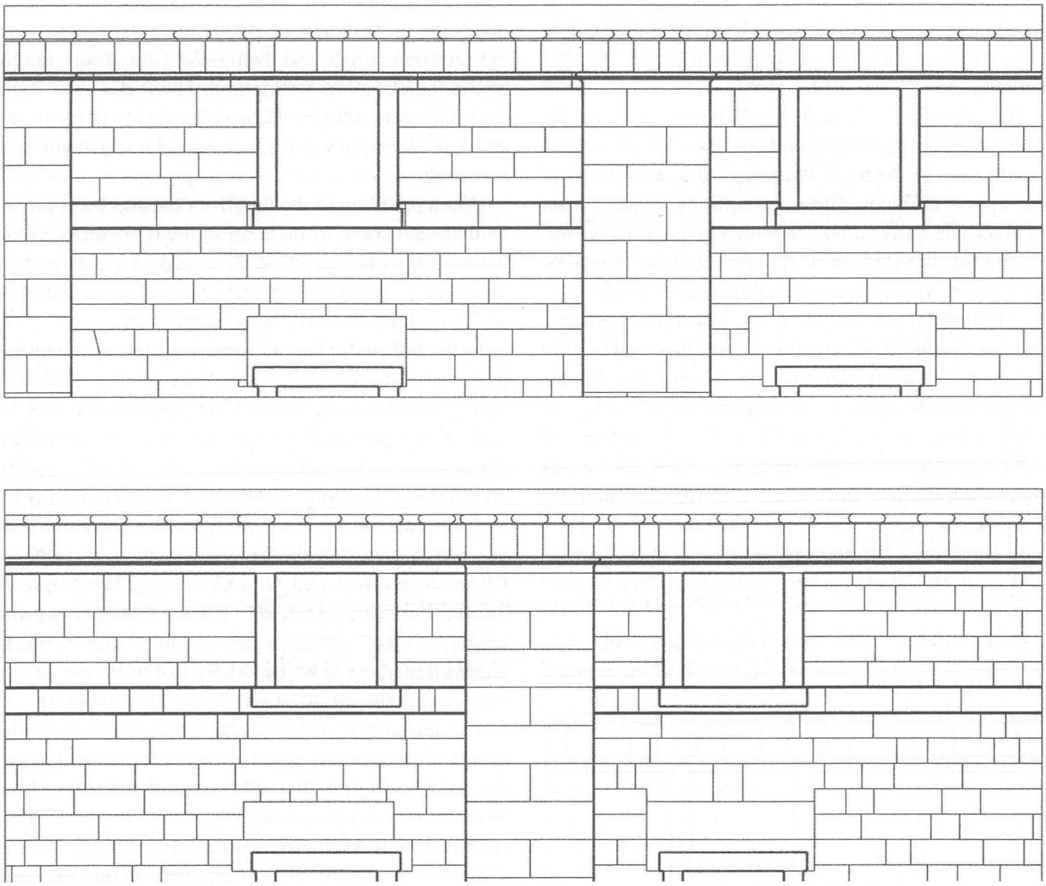

Figure 7

the west façade, where the rows are ostensibly higher or lower than the norm. In general, in the west façade, there are more constructive irregularities, deriving from less harmonious, and less exigent work. Referring to the heights of the rows, it must be added that, in the centre, where a composition proper to the façade of a temple is observed, the execution is more carefully carried out, (and thick joints filled in with mortar and pieces of slate are not seen as in the rest), but the pieces of wall section enclosed at the top do not continue the rhythm of the rest of the wall sections.

The false or dissimulated joints, however, are not limited to the area of the suppressed pilasters. At the bottom of west façade, the presence of one-pieced parapets, upon which the false joints continue the design of the wall, is noteworthy (Fig. 9).

Here one could add the irregularities that you have observed. There also seems that there is a certain continuity of vertical joints, as a constructive limit, in the space that there is just to the left of the last windows with a full parapet.

SOUTH FACADE

Here the disorder increases, especially in the bottom half, contrasting notably with the apparent harmony which has characterized the monastery. Exception must be made of the asloped base, which follows the

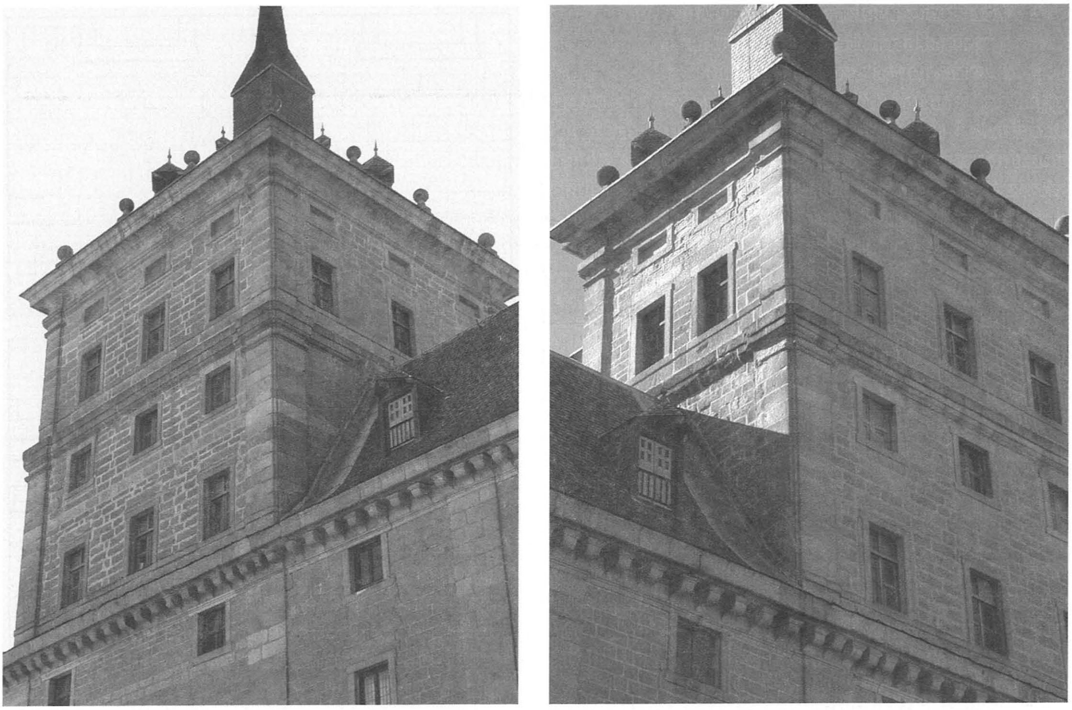

Figure 8

entire facade, completely uniform and perfectly carrried out, although the height of the rows has been adapted to the composition of its moldings and spaces.

The rows vary frequently from the standard one-foot height. Their dimensions vary continually, and it is not difficult to find joints that visibly lose the

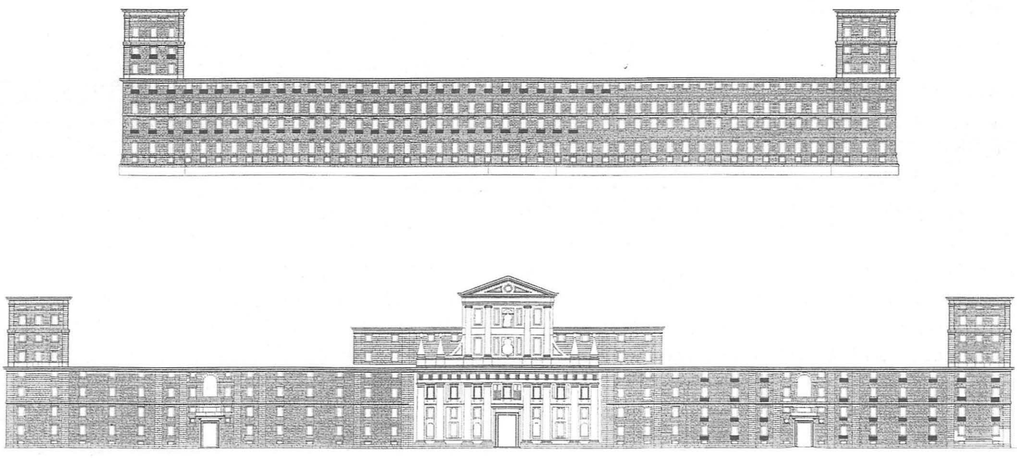

Figure 9
One-pieced parapets, in west and south facades

horizontality or that recuperate it abruptly with one step (Fig. 10).

On the left, the spaces are not finished off with a full lintel, rather a relieving arch. As you proceed to the right, flat arches replace the bearing arches (Fig. 11).

On the left, under the tower, one can see an ample zone of false or dissimulated joints (Fig. 12.) The correction seems to have no other end than to hide the excessive height that one of them has.

In this same area, the stone parapets of the second and fourth row of windows are made of only one rectangular piece with false joints, as in the lower spaces on the west facade (Fig. 9). This does not occur in the entire façade, but in a great part of it: in the second row from the extreme left up to the second

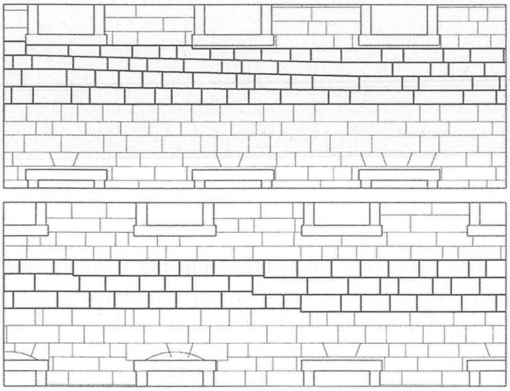

Figure 10

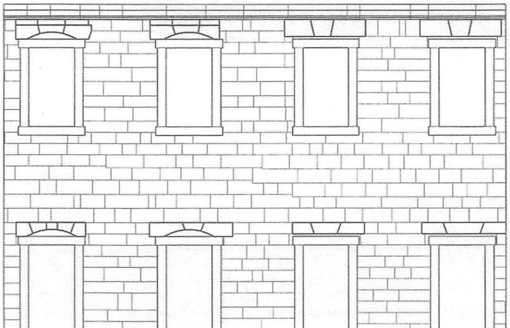

Figure 11

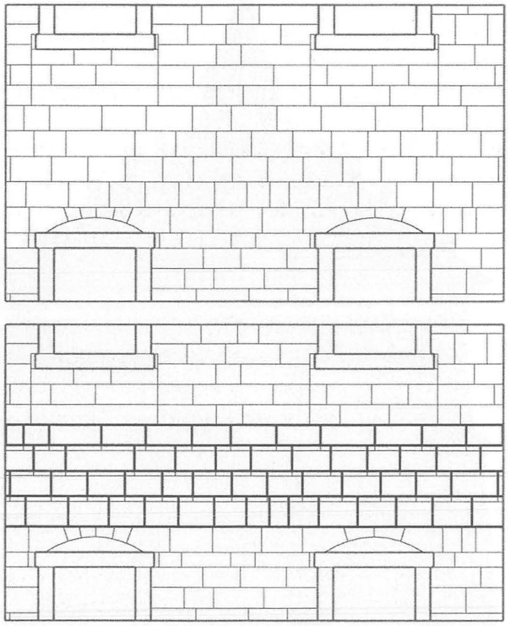

Figure 12

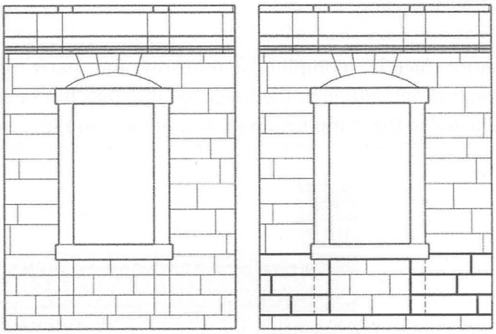

Figure 13

window after the original central tower, and in the fourth row up to the fourth window after the tower.

These great pieces reach from the width of the space, including the door jamb; in one of the spaces, however, the entire piece is limited to the free light of the space, furthermore, here one can see the signs of some jambs that went down to floor level (Fig. 13), as if at some moment one had thought of designing a

space equal to that of the third row with a banister, or a similar space in which the wrought iron banister would be substituted for a piece of stone.

Under the cornice, there is a band which becomes a lintel of the windows of the top row, as occurs on the other facades. When pilasters exist, this band links to them. Nevertheless, on the south façade, to avoid reaching the corner, the band disappears a little before, as it planes down little by little (Fig. 14).

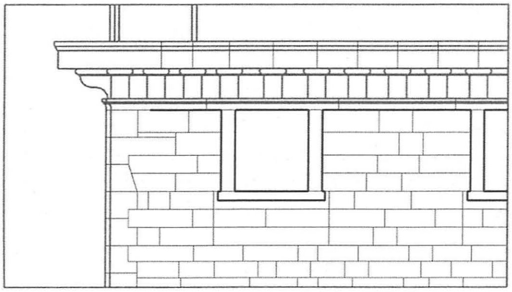

Figure 14

The suppressed tower separates the façade in two parts and the horizontal separations between the windows are slightly wider to the left than to the right. As a consequence, the three windows are not centered in the left tower.

Counting from this suppressed central tower, between the fourth and fifth space, that is, coinciding with the end of a series of full parapets, the vertical joints coincide, especially at the bottom half, which makes one think of a provisional vertical limit. But, in addition, this construction joint has become a crack in the wall, which, at the mercy of settlings, has broken at the weakest line (Fig. 15).

Comparison

In general, greater indecision in the south-west zone, where the work was begun, is evident, as is a greater regularity in the north, where the work ended. Juan de Herrera's changes made the work proceed faster and more harmoniously.

However, as we have seen, the north facade originally presented some constructive irregularity.

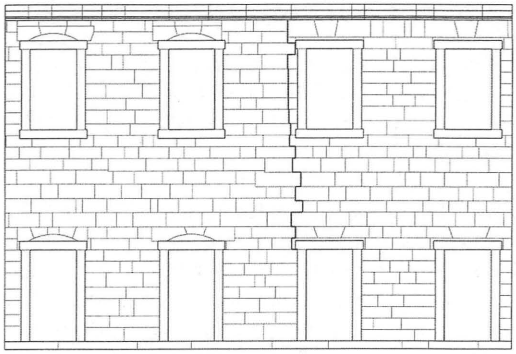

Figure 15

Inside the basilica, to the contrary, the heights of the rows are more rigorously kept. In fact, there is a row which is ostensibly lower and follows all the interior parameters of the temple. If we follow it carefully, we can observe that it corresponds to the lower part of the band which delimits some decorative rectangles above the arches of the lower floor. That is, the bond was carefully adapted to the molding, which was not so necessary in the exterior.

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The single coursed ashlar vault

Enrique Rabasa Díaz

A spherical vault, whether a hemisphere or a sail vault, is formed of voussoirs. The voussoirs are typically arranged along circular horizontal rows, separated from each other by conical surfaces that are more closed as we advance toward the pole and whose vertex is always the center of the sphere. Within the same row the voussoirs are all equal or similar and they are separated by joints following vertical planes which converge on the central axis. In this way each piece has a spherical inner surface, two top and bottom bed joints that are cones, and two joints that are vertical planes. In the unusual case that the piece appears on the extrados (exterior) of the vault, then the exterior surface could be spherical as well (figure 1).

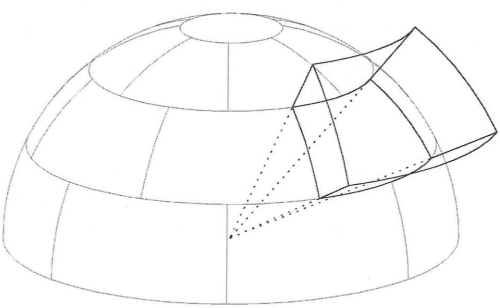

Figure 1
Conventional voussoir for a spherical vault

We find many exceptions to this geometrical division, though most involve slight variations from arranging the parallels and meridians in a different spatial position (Fig. 2). In effect, the sail vaults —those that are sectioned by four perimeter arches in order to adapt to a square foundation— on occasion present a geometry that in the 16th century was named «por hiladas cuadradas» (for its square courses), and that, as its name indicates, arranges rows in a square horizontal projection, each time smaller until closing the surface. Each of the sides of these square courses is a vertical row equal in all ways to those described above. So we have here a division also according to parallels and meridians, although with the axis placed horizontally.[1]

The usual procedure in the 16th century for the carving of the voussoirs of a spherical vault is as follows. Over a block of stone from the quarry, one would first carve the inner concave surface of the vault (intrados), the one which will remain visible, but not starting from its definitive edges, but rather working a portion of spherical surface, to afterwards mark on it the real contour. This operation, the definition of the contour of that face, would take place applying over the face a template, as is typical in the work of stonecutting. However, as is known, a spherical surface is not developable, so the application of a flat template over the sphere is only approximate. In any case, through this one would proceed to the carving of perimeter, bed and vertical joint surfaces.

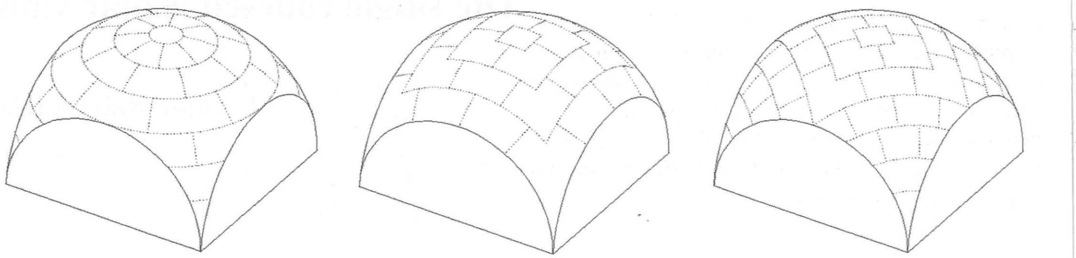

Figure 2
Various arrangements of the joint according to parallels and meridians.

As we have said, this involves different surfaces, two cones and two planes, but all can be considered as surfaces generated by the movement of a radius of the sphere, following parallels in the case of the conical beds and meridians in the case of the planes. Therefore these four surfaces can be carved with ease employing an instrument called a bevel. The bevel is a type of square that has a curved piece that adapts to the concavity of the inner surface and another straight branch that follows the direction of the bed joint towards the center. Its use is common in the carving of the voussoirs of the arches, as it allows proof of the orthogonality of the inner surface and the bed joint and the correct execution of both. Its application to the spherical voussoirs is a brilliant idea, as it determines the shape of more complicated pieces than those of an arch.

Finally, if it were necessary to carve the exterior, one would mark its contour tracing a line parallel to that of the intrados and confirming the carving with a concave curved ruler or a concave bevel.

This procedure is of the type that we call direct, as opposed to those that pass through a previous squared-up stone beforehand. In the 18th century variations on the use of the template for the spherical voussoirs were proposed and also the procedure of the squared-up stone was proposed, but there is no doubt that in Spain in the 16th century the usual procedure was that which I just explained. That is what is shown in the manuscript of Alonso de Vandelvira, and with more detail in that of Alonso de Guardia, at the end of the century or beginning of the next, and the book of Francois Derand or the manuscript of the Catalan Joseph Gelabert, in mid-17th century.[2]

We now return to the template of the intrados. Made up of brass or cardboard, it should allow a certain curvature to adapt to, although imperfectly, the spherical surface where it is applied. It is in reality a small piece of an approximated sphere. A sphere can be developed approximately if we suppose that it is divided in segments according to meridians (Fig. 3), and we liken each one of these segments to a portion of the cylinder. It is a procedure employed in cartography. We can also divide the sphere in horizontal sections according to the parallels, and substitute, in each sector, the spherical surface for the trunk of cone. These cones, more or less open, have their vertex always on the axis of the vault. This is the

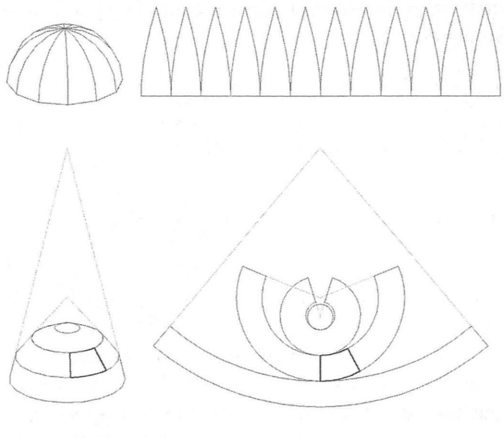

Figure 3
Developments of the sphere according to cylinders and cones

aproximation chosen by the stonecutters (the approximation of the segments also will be employed in certain occasions, especially for the design of the decoration.) Each one of those cone sections are easily developed tracing the corresponding arches with the center in its vertex (Fig. 4). The template of each voussoir is no more than one part, more or less large, of this development.

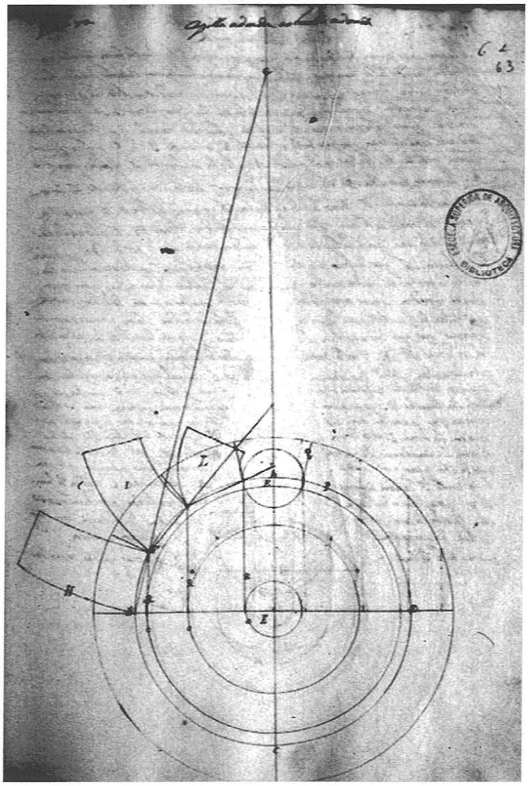

Figure 4
Layout for a dome in the treaty of Vandelvira

The prepared template would be applied over the spherical inner surface of the vault to mark its contour. If we were very strict with the geometric concepts, we should take care that the template touches the surface only in the edges corresponding to the parallels, remaining separate along of the other two sides (fig. 5). But the practice shows that, even in vaults of small span and great curve, this precaution

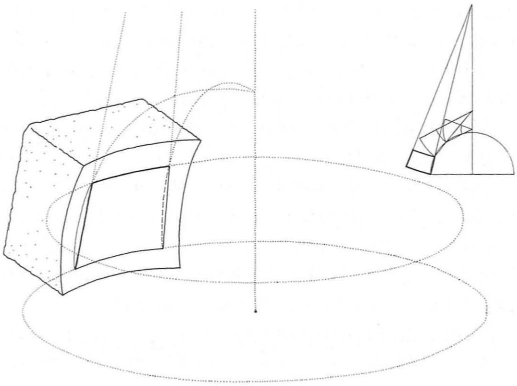

Figure 5
Adaptation of a flat template to the spherical surface

is excessive, and the stone-cutter commits a little error if he applies the template flattening it without care so that it remains in contact with the stone.[3]

Thus it happens that, finally, the use of the template and the bevel very easily solves the work of carving the voussoirs for spherical vaults. The stone-cutter would require a different template for each row, but the templates, and the pieces, of a single row are all the same. Even if the vault is not very small, the voussoirs of each row can be of different longitudes, according to the dimensions of the blocks that the quarry provides, but its templates always have the same form, more or less extended (or applied successively).[4]

There are another type of hemispherical vault, that presents just one helicoidal row, named by Philibert Delorme «en forme d'une coquille de Limaçon» (De l'Orme 1567), and by Alonso de Vandelvira «en vuelta de capazo» (Barbe-Coqueline 1977). However these two authors do not develop the problem in the same way.

The concept is, in principle, different from those explained, because it starts from another possible development of the sphere. It involves something easily conceivable in so much as it is similar to the peeling of a fruit. From the geometrical point of view it is something more complicated. As before when we signaled parallels or meridians and between them we substituted the sphere for cones and cylinders, now we should trace a helicoidal line over the surface of the sphere, —something that can be done a few

different ways—, and to support between each two turns of the helix a ruled developable surface —for which there is only one solution, but is not as simple nor evident as when it involves cones and cylinders.

The drawing that we find in the vault *en limaçon* or like a snail, of Delorme (figure 6), reappears almost exactly in the manuscript of Jean Chereau (1567–1574) (figure 7). Chereau copies many solutions from Delorme; in this case it is done in a literal way, evidently without understanding the problem, as it duplicates the same mistakes.

In effect, the two drawings trace a spiral in plan, and that spiral is projected vertically in the spherical surface. The spiral of the base is drawn in such a way that the progression of the line in each revolution is constant. Consequently, the height of each row is continually variable. As happens in other layouts of hemispherical vaults, in the layout of this vault we have the benefit of the same circumference for the base and the section, in such a way that in the upper

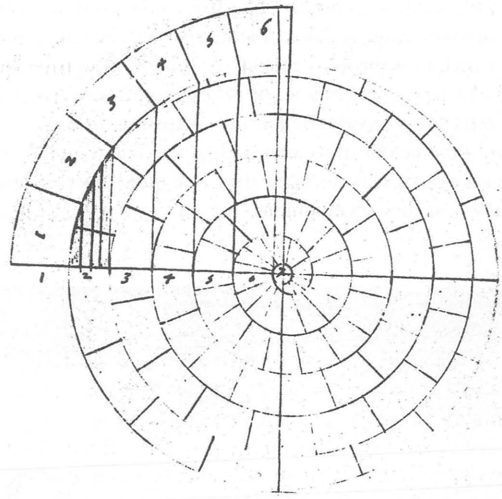

Figure 7
The vault *en limacon* in the manuscript of Jean Chereau

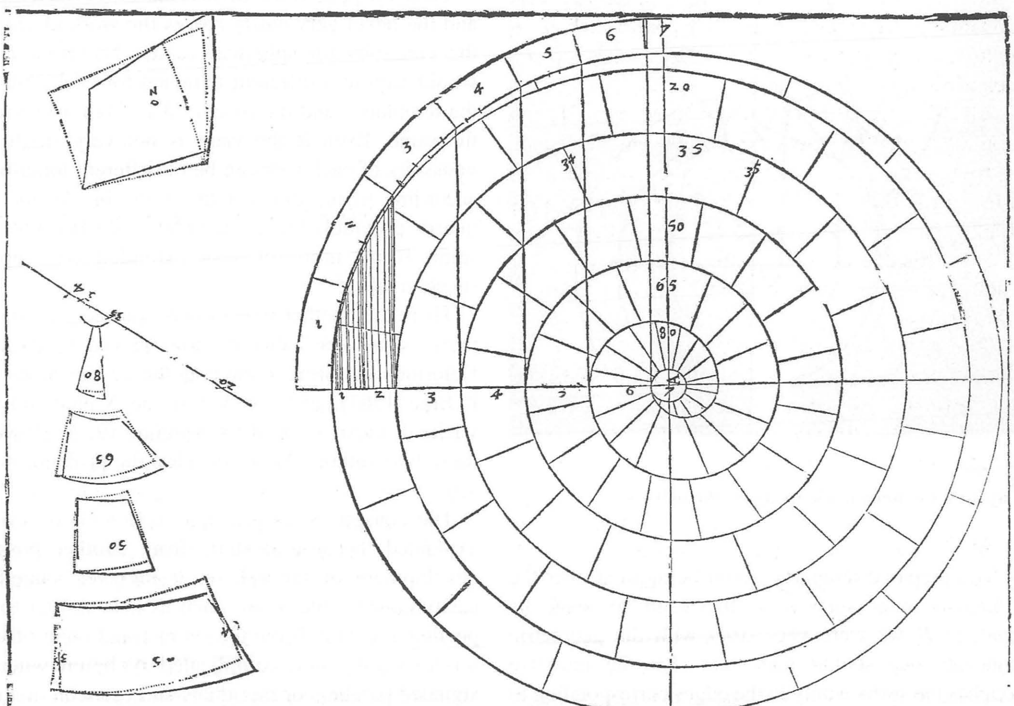

Figure 6
The vault «en forme d' une coquille de Limacon» by De l'Orme

left quadrant we can see the semisection, that projects the partitions of the base vertically upwards, and shows that the height of the row increases from the pole towards the equator. Precisely from here is where the most important error of the layout originates: the heights of the rows resulting in the upper part, numbered 6, 5, 4, 3, are different but moderately so, whereas the height that would result in the base of the vault is notably greater than the rest, so that the author (both authors) have decided to divide this first height (1 and 2) in order that it becomes similar to the rest. Evidently this is not a well-defined solution, because, although we decide to begin with that divided row, at some point we will have to return to just one piece, etc.

It is certain that the text of Delorme alludes to the possibility of employing the same layout to design of a conical or spherical vault —although the text speaks of a «pyramidal» form, it is to be assumed that it refers to a cone, as it involves, it says, covering a *tour ronde* or a spiral staircase. In the case of the cone, the spiral of the base would have projected onto something very approximate to an ordinary helix of constant step. But the drawing clearly develops the spherical option.

So then, the drawings of Delorme and Chereau contain operations that any craftsman who really faced the problem would have rejected: to think about the spiral directly like a tracing in plan then transferred to the space, to accept a row of constantly variable thickness, and to solve the problems that these decisions generate with unskilled and undefined clumsiness.

We examine now the layout of Alonso de Vandelvira (fig. 8). This author draws the spiral of the base from the point of the spatial helix that he wants to obtain. The process consists of first determining the height of the row by dividing the section as if it involved a conventional hemispherical vault in order to afterwards make those points of division rotate around the axis at the same time that they uniformly advance towards the pole by their meridian. Vandelvira divides the circle of the base in equal parts (16 of them) and divides the height of the row in the same number of parts, projecting them horizontally, in order to trace the spiral line in plan. Each unit of revolution corresponds to one part of nearing the center. The layout is, naturally, a flat drawing, but it corresponds with a spatial conception of the line.

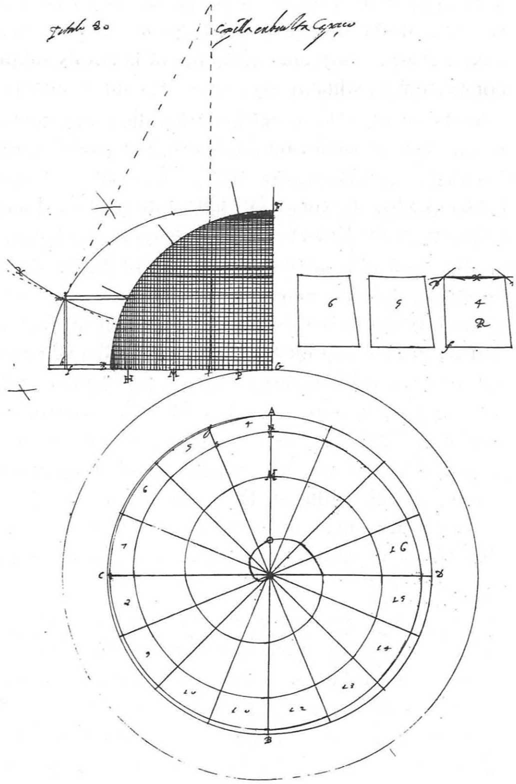

Figure 8
The vault «en vuelta de capazo» in the treaty of Alonso de Vandelvira

As a consequence, in Vandelvira's layout the height or distance between the lines of the upper and lower bed joints is constant. This helicoidal solution of the spherical vault is characterized by its unnecessary complication, in that it is unavoidable that all of the pieces will be different; but, within this general inconvenience, Vandelvira's layout departs from reasonable assumptions and attempts a certain uniformity, while that of Delorme arrives at an absurd solution.

On the other hand, neither Delorme nor Chereau say anything concerning the templates for the execution of the pieces. Delorme draws them, and it seems that he obtains them starting from a theoretical template of conventional model, but, as is common for Delorme, he doesn't explain anything. Although

the layout that Vandelvira proposes to obtain the templates could be criticized from a strictly geometric point of view, at least the author undertakes and clearly explains this theme.

In effect, we have confirmed that the template for the carving of a conventional spherical vault results from the development of a section of cone approximating the spherical surface. In this case there is no cone as a substitute for a portion of the sphere. Is unlikely that Vandelvira conceived of the the ruled developed surface mentioned before as a possible approximation to the sphere. So that, in this case, as in others of his treaty, he would obtain the more or less quadrangular template in a very approximate way, looking for the distances in real magnitude between the vertices and joining these vertices with lines reasonably near to the straight or curved lines that we intuitively should obtain.

The intrados have four corners, four vertices in its template, that will not be over the same plane. After estimating the distances of the four sides, we will have to choose one of the two diagonals, as each one will result in a different quadrangle. Consequently, what Vandelvira does is not a development, but nor can it be said that it is the real form of the relative positions of the vertices. The obtained template could be of value if it is folded by one of its diagonals, keeping the two parts level, about which Vandelvira says nothing. Therefore, the triangulation that Vandelvira uses in order to draw the relative positions of those four points implies a geometrical approximation. On the other hand, this template will be similar to the conventional in that the lines of the lateral joints will appear straight, but the superior and inferior sides, corresponding to the bed joints, are now developed from the helicoidal line and not from circular arcs. Vandelvira draws them, however, as circular arcs, and it is curious to note that, in doing this, he does not consider something similar to the cone that passes through the superior and inferior lines, rather he invents a hypothetical tangent cone for each one of two parts of the helicoidal line. As a consequence, the superior edge of a template coincides with the inferior edge of the template of the piece that goes above it, which theoretically could not occur, as Vandelvira occupied himself with explaining in reference to the hemispherical vault.

It should be recognized that Vandelvira takes many licenses and departs much from what we now would understand as a strictly correct solution, but also that the posed problem was enormously difficult given the knowledge of that time, and, in this situation, Vandelvira makes a correct use of some resources, finding real magnitudes, imagining hypothetical cones, etc.

In fact it is very notable that, when the conceptual tools capable of solving this problem did become available in the 19th century, in contrary to what we would expect, no one attempted the problem at all. The helicoidal joints of the dome are not even mentioned. We might assume that the stereotomy of the 19th century rejected undertaking an unnecessarily complicated problem; however it is clear that they did engage in studying other rather absurd and sophisticated proposals. The reality is that the correct execution, which demands the determination of the ruled surface and its development, would be complex and not very elegant from the geometric point of view.

It is worth noting that this type of vault appears in the copy of the treaty of Vandelvira conserved in the Escuela de Arquitectura de Madrid, but not in the copy kept at the Bibloteca Nacional (by Felipe Lazaro de Goiti).[5] Vandelvira presents this vault as a variant of the *vuelta redonda* or conventional hemispherical vault, and in the copy at the Escuela de Arquitectura it appears after the collection of ribbed hemispheres. The copy of Felipe Lazaro de Goiti omitted all of the ribbed vaults, as much the gothic ones as the rib and panel vaults (*enrejada*), probably thinking that they had to do with an old tradition. If this type of vault (*vuelta de capazo*) was situated in the original as it is in the copy at the Escuela de Arquitectura, that is to say, a continuation of the rib and panel vault hemispheres, it is not strange that it would be left out together with this group.

Perouse de Montclos (1981) explains that this particular method and other similar games are no more than unrealized fantasies of Delorme and Chereau. It is certain that we do not know of any French examples, and, in any case, it is evident that the drawing of Delorme/Chereau can not have any relation with a real example that was known very directly by them, because as I have argued, it presents important practical problems.

Similar layouts of spirals in a circle are found in the manuscript of Hernan Ruiz el Joven; it is not clear, however, if this is a layout for a vault of this type,

since it involves Archimedes' spiral (in some cases the integration of a few), that open or separate progressively as they depart from the center, which would notably exaggerate the defect found in Delorme. It would be possible, however, to have a relation with the ionic volute; in fact one of these spirals is applied to this function. In any case, the usual layout of the ionic volute is a spiral ready-made with circumferential arcs, of diverse centers, starting from an initial small circumference.

I have commented that the way to trace the spiral of the base in Delorme/Chereau allows the step to be constant. This is done with a layout very similar to that of the ionic volute, employing circumferential arcs. In this case it started from the circle of the central keystone, employing the two points of the circle that coincided with the horizontal axis. The spiral begins then with a first semicircular arc from the center of the left, continues with another semicircular arc from the center right, etc. It is easy to verify that in this way the distance between turns is constant and equal to double the diameter of the keystone. We can also find a spiral of two centers in Villard de Honnecourt's notebook, which has been put in connection with the layouts of pointed arches (Bechmann 1991, 225–230).

The type of the vault *de capazo* (or *en limaçon*) appears later in the book of Milliet-Descales (1674), figure 9, and in that of T. V. Tosca (1707), figure 10. It is known that Tosca also copies Milliet-Deschales in almost all of his exposition on the geometry of stonecutting. In this case the original French layout is as problematic as that of Delorme, and Tosca's copy is even worse.

In effect, Milliet-Deschales lays out a spiral even more similar to that of the ionic volute, as it employs four centers, the four axial points of the initial circle, but in doing this obtains, as in the case of the volute, a progressively wider step as it departs from the center. In this way the problem of the row's height is made worse, and the author no longer occupies himself with drawing the section, where again the first row would appear disproportionately taller than the rest.

Tosca copied the drawing, which is identical in a multitude of details, but takes two centers, and these points are, unlike those of Delorme, one on the cercle (that is marked I) and the other in his center. In this way there are not four circumferential arcs in each

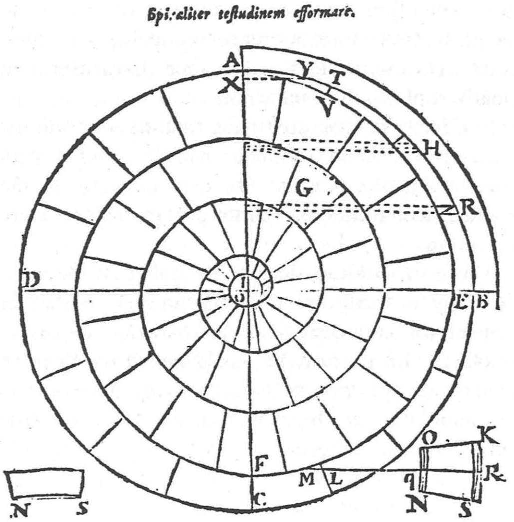

Figure 9
«Spiraliter testudine efformare», by Claude Francois Milliet-Deschales

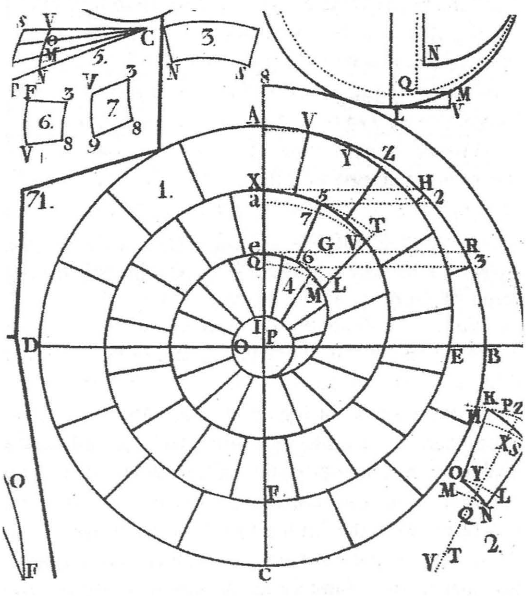

Figure 10
Hemisphere that closes «a manera de rosca», by Tomas Vicente Tosca

turn, rather only two, and one of them is traced from the center of the circumference, producing concentric semicircles with it. So then, the spiral form is achieved in Tosca in the strangest of ways, since the half of the base is exactly like a vault of conventional round rows, while the other half is charged with constructing the helices. The text just refer to the layouts of conventional spirals, as if the subject were irrelevant.

These two authors draw the template of the vault faces by a somewhat different process to that of Vandelvira, although also approximate, departing from an ideal straight template. The Spanish manuscript of Portor y Castro,[6] copying Tosca, offers the same drawing (Fig. 11). I do not know of other layouts for this pattern.

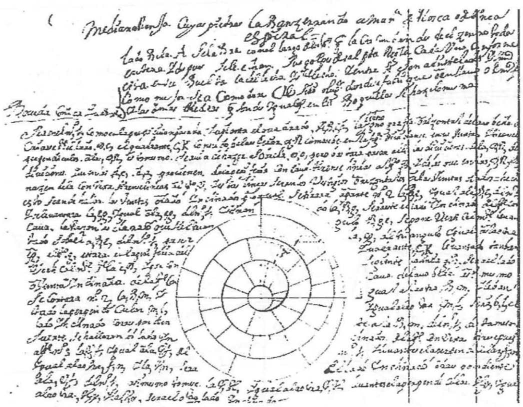

Figure 11
Hemisphere that closes in «a manera de rosca o de linea espiral» (in the way of rosca or of a spiral line) by Juan de Portor y Castro

So then, this suggests a stereotomy method conducted by the French theorists, in all cases probably from the point of their diffusion by Delorme, copying it (Chereau) or trying to improve it (Milliet-Deschales). A certain branch derives from Milliet-Deschales by the copy of Tosca and of Portor. It is difficult that none of these authors really put into practice their execution, given the removal from reality that their processes show. The layout of Vandelvira, without any relation to the former ones, is on the contrary, that of someone who perfectly dominates the real problems of this pattern.

In a space next to the the vestry (*antesacristia*) of the Murcia cathedral we find an executed example of this type of vault (*de capazo*), figure 12, that shows a row of constant height, like in the case of the layout of Vandelvira. Its surface is «wrinkled», as it was intended to receive a subsequent finishing, except in a detached molding along the helicoidal line of the bed joints. Perhaps this concealment of the radial lines was meant to cover the small defects that a layout as problematic and necessarily approximate would need to endure.

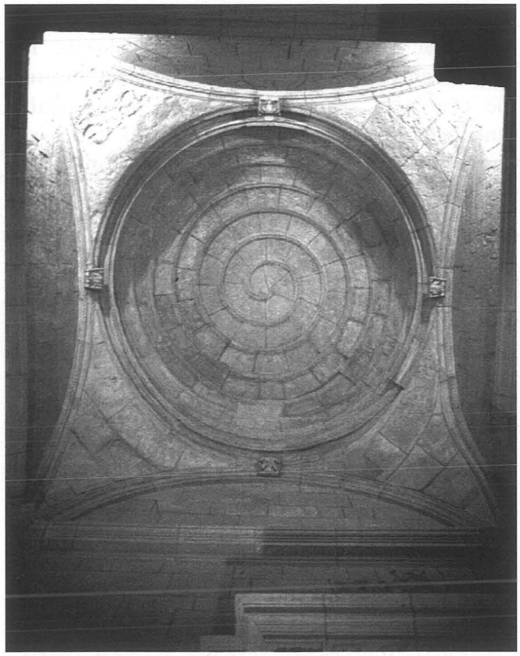

Figure 12
Vault *de capazo* in the Murcia cathedral

Despite the geometrical analysis that I have made, we have to recognize that, as much in the conventional round row semi sphere as in this helicoidal variant, the real and practical demand of precision in the form of the pieces is not required. The French solutions and their derivatives committed such important errors that it is difficult to imagine a

practical solution along such models. But that of Vandelvira, despite its multiple approximations and licenses, offers a buildable pattern. This is espacially true if we keep in mind that accepting approximate solutions was a habitual custom in the stonecutting of the 16th and 17th centuries.

Greater demand for precision is require for another of the examples of this type of vault found in Spain, the one situated in the spiral stairway, named *caracol de Mallorca*, that leads to the right tower of the Palace of the Guzmanes de Leon, figures 13 and 14. The two towers of this principal façade are recent reconstructions of a somewhat austere aspect, but the stairway, crowned by a vault with a decorated hanging keystone, is evidently original, and therefore dated to the second half of the 16th century and subsequently to the Murcia. As its dimension is much less than that in Murcia, the shaping of the voussoirs demands somewhat more precision. In this case, the helicoidal line of *caracol de Mallorca* continues ideally in the covering that finishes it off. It is notable that the text of Delorme makes mention of the possibility of covering a round tower or a spiral staircase with these vaults. And that the layout of Chereau presents this vault on the same page as the *vis de Saint Gilles*, spiral staircase covered with a helicoidal barrel vault.

Figure 13
Spiral staircase in the Palace of the Guzmanes de Leon

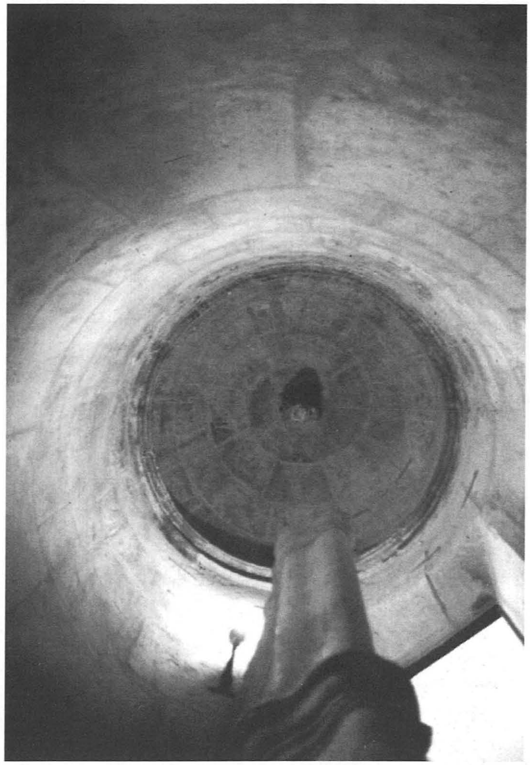

Figure 14
Dome that covers the staircase

Finally we know of another even later example. It involves the church of San Juan de los Caballeros in Jerez de la Frontera (Pinto 1998), figure 15. The vault is situated in the portico and covers a rectangular space of 1:2 proportions, so that the helix is found whole only in the very small central part. But its greatest peculiarity is that it doesn't involve just one, but rather two simultaneous helicoidal rows, that arrive at the center, avoiding therefore a polar piece.

On the other side, in this same façade we find a most curious example of *vis de Saint Gilles*. So the relation between the spiral staircase and the vault *de capazo* continues.

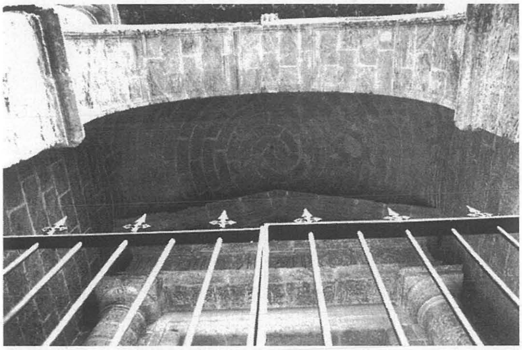

Figure 15
Helicoidal vault in the portico of San Juan de los Caballeros in Jerez de la Frontera

We don't know the origin of these patterns. Although the proposal of Vandelvira may be much better and more real than that of Delorme, nothing impedes that it be this drawing first that, widely published, would provoke interest in Spain. It doesn't seem that the Florentine tradition of drawing helices in the brick domes would be relevant; it involves loxodromical curves generated by a herringbone pattern, and they are different from the vault *de capazo* as much constructively as formally. We should consider, however, two other possible influences. On one hand the Byzantine tradition of execution of spherical vaults with ceramic pieces prepared along one or various helicoidal rows. This is, for example the dome of San Vital de Ravena. And furthermore we know of the existence of an example in stone much earlier, in Anatolia.

In effect, the Sultan Han near Aksaray (1229), figure 16, was built as a rest area for the caravans, with commercial and religious function. As usual for this type of construction, it has a bedroom space of great dimensions, similar to the Christian temples, and formed in this case by five naves separated by columns and covered by barrel vaults. In the center of the principal nave was constructed a vault of this type, over squinch arches covered with a pyramid also of stone. Its architect was originally from Damascus; it is unavoidable to record here the opinion of Viollet-le-Duc, who was convinced that all Westem stereotomy had its origin in the admiration of traveling Christians towards the patterns of the Syrian construction. There are at least two other small domes or calotas, of reduced dimensions, with this type of pattern, covering the central part of domes in the hospital annex to the mosque of Divrigi, that date also to the 13th century.[7]

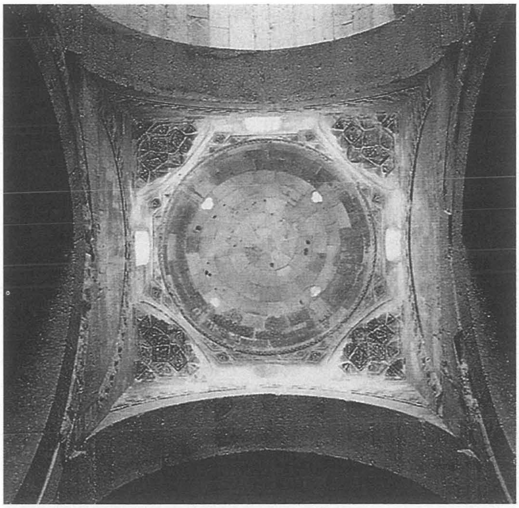

Figure 16
Dome in the Sultan Han near Aksaray (Turkey)

Finally we have to remember that this type of pattern is a solution enormously more complex than the conventional solution for a hemispherical vault. In effect, the solution by round rows demands only one template per row, and in each row the pieces are equal. Common sense leads Vandelvira to adopt a uniform height for the helicoidal row, but even so the pieces and all of its templates are different and require an individualized layout. It is to be supposed that in practice the constructed vaults were made with an added license to those other geometrical licenses already explained: since the design of all of the templates would be laborious, complicated and susceptible to confusion, one would employ the same template to a whole series, maybe to all of the ashlars in one turn of the helix.

In any case, the idea of the helicoidal row, which is reasonable in brick or ceramic pieces, becomes unnecessarily complicated in stone. That isn't the only case. Often more complicated and difficult patterns than the conventional ones have been proposed. But this, which happened especially in the 19th century, frequently was done with the intention of showing an elegant idea from the geometric point of view. Or rather, as occurs with the curious variants of waterspouts between the 16th and the 18th centuries, in order to develop a showpiece of a mechanical more than formal type. In this scope the vault *de capazo* is a very early and atypical example of this unnecessary complication. Maybe the intention of introducing the helix archetype in the stone work existed in some examples, but very probably the mentioned cases are displays directed to the stone-cutting guild itself.

NOTES

1. If one were to look for a difference, it could be found in the corners where the pieces, in the shape of L, correspond to two rows. Although frequently, including at El Escorial, this form is avoided and the pieces of the corners would be resolved in a similar manner to the rest.
2. I have justified these statements in Rabasa (2000).
3. I have confirmed that this is true in the construction of a small dome in collaboration with the Centro de los Oficios de León. It had only a one meter span, but for that very reason the pieces have great curvature.
4. If all of the voussoirs of a row have the same length, the template is made for this size. But if the dome is large, the distribution of joints is not established in advance, and each piece has a different length, adapted to the size of the blocks from the quarry. In this case the template is easily slid over the surface of the stone to mark the perimeter of the face of intrados when the length varies.
5. It is the manuscript Ms.12.719 of the Biblioteca Nacional de Madrid and R.10 of the Biblioteca de la Escuela de Arquitectura de Madrid, that is a reproduced facsimile by Barbé-Coquelin (1977).
6. Manuscript from 1708, conserved in the Biblioteca Nacional de Madrid with the call number Ms. 9114.
7. I am grateful to Profesor Aysil Yavuz for calling this to my attention. Drawings of these vaults can be seen in Yavuz (1993, 165–192).

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Examples of some late antique building techniques, applied on the *horreum* from *mediana*

Ana Radivojević

Historical circumstances in the time of late antiquity were such that the interest of the Roman world has roused and transferred towards the eastern pole of the Empire. Many very important rulers of that time were of the origin from central Balkan provinces. Consequently, this particular region, previously concerned only as a border, provincial part of the state, transformed into the place of a special interest. This was followed by the expansion of building production, which was very often of high administrative, or even imperial significance and function.

One of the centers from the mentioned provinces, which had lived the period of its highest prosperity in the time of late antiquity, was *Naissus* (nowadays Niπ). One of its parts was the neighboring agglomeration, *Mediana*, famous by many highly representative villas and other buildings that were forming it. One of the particularities of this site is the presence of numerous immense buildings that certainly were of some higher importance in the region.

During many years of archaeological excavations of this site, ruins of a building that was recognized as a granary, or *horreum*, were discovered practically in its total plan. The remains presented the building exceptional both by its size (27 × 90 m), as well as by its function and organization. Consisted mainly of the huge storage space, with the porch in front the main entrance, auxiliary rooms and separated administrative part, the *horreum* was dated in the beginning of the IV century AD, like all the other buildings of this archaeological site. Two rows of eleven large stone posts for the pillars that were made of bricks have divided the main part of the building into three naves. Between them, several 2m high containers, called *pitos,* partly buried into the ground, were found, some of them completely preserved. In one of the later phases of the building, in the western part of the storage, three pits, carefully plastered with mortar that contained crushed brick aggregates were dug into the ground. Their use was explained as containers for oil of other liquid materials that could have been stored this way.

Although the remains of the walls and piers were scarce by its height, the plan of the building could have been defined. Found in the soil, traces of burned wooden structure, connecting metal elements and other indicators of the architecture of the former building were recorded during the excavations. This offered enough elements to review and compare different building techniques applied on this building with those of late antiquity, and enabled the creation of possible ideal-reconstruction of some particular parts of the granary, as well as of the whole building.

HISTORICAL BACKGROUND

Roman civilization whose influences have been spread over the territory of almost the whole Europe

and Mediterranean countries, has left rich cultural and building heritage in the Balkans. One of the cities that represented a significant regional urban center of that time was the ancient *Naissus*. Our knowledge about it is based on different historical sources, such as written documents from authentic period, epigraphic monuments and archaeological findings, representing a material proof and visualization of historical facts and assumptions. According to them, foundation of this city is connected with the foundation of the Roman province of Upper Moesia in the I century AD. Its position on the crossroad of the main routes that were bringing eastern and western parts of the Empire together, resulted with its important strategical and military significance, due to which this Roman town lived its ancient phase of life till the very end of late antiquity.

The period that is considered as the most prosperous time of *Naissus* was recognized as the IV century AD. Ever since the reign of Diocletian at the end of the III century, erection of the most important buildings of this town has begun, both in *Naissus* itself and in its neighboring parts. One of them was *Mediana* whose function was often explained as «the luxurious suburb with villas». Regarding the urban organization of this settlement, it is certain that its central position could be identified with a unique villa with the peristyle, Figure 1, which was often considered even as an imperial palace, or at least the place where Constantine and some of his successors used to reside during their visits to *Naissus*. On its east, north and south, there were traces of the existence of other luxurious representative buildings, while on its west there was a large economic complex consisted of huge workshop buildings and an immense granary. Although the organization of this settlement could be described as the one of the open type, there was a fortification in its rear, placed on the «Vlaπko brdo» hill.

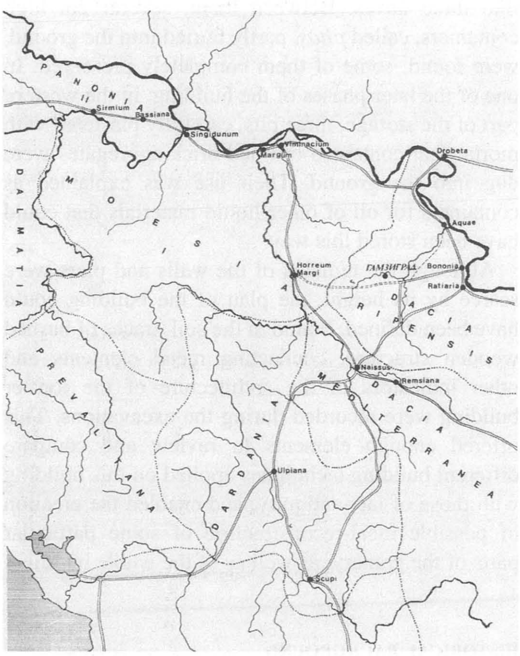

Figure 1
Location of *Naissus* in Roman Empire at the end of III century AD

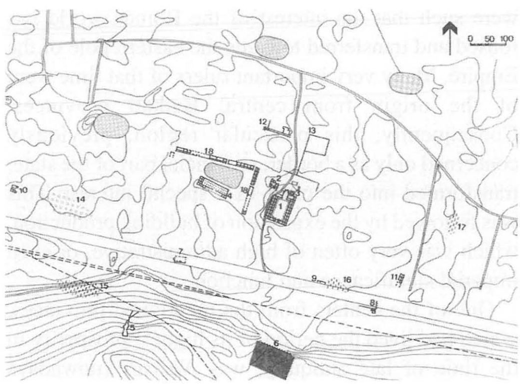

Figure 2
Situation plan and disposition of the buildings in *Mediana*

THE GRANARY BUILDING OR *HORREUM*

Traces of the huge building representing a granary were discovered during the first archaeological excavations of *Mediana* in 1936. when its north wall was revealed, as well as the east end the inner space of the building, including remains of the stone posts for the pillars and large pots called *pitos*. During this first archaeological campaign, a western part of the building was also partly dug, in which evidences of three pits used as containers for oil or similar goods,

were discovered. Excavations have continued many years afterwards, first in 1961, and then in the period from 1980 till 1983. Nowadays we can say with the great probability that the granary is known in its total area.

Figure 3
View of the remains of the granary

Three chronological phases of the building were discovered during archaeological excavations, although, according to the applied building material and building techniques, there was not a big interval between the building phases. Therefore, they could be probably considered as a kind of adaptation of the building during the long and continual term of use. It is believed that this building, which, the most probably, was destroyed in fire during the invasion of Huns in the mid of the V century, has never been reconstructed again.

Organization of the building

The granary building has an elongated trapezoidal plan. Its width was 27 m, while its longer, parallel sides, were oriented in the northwest-southeast direction. Due to the shape of its plan, the length of the longitudinal walls varied from 89,5 m (north wall) to 92 m (south wall). The main part of the building, which was built in the first building phase, is represented in the elongated storage space, 18,5 m wide. It was divided with two rows of eleven masonry pillars in three almost equal naves. Square pillars had their posts (approximately 1,5 × 1,5 m), made of cut blocks of stone, while they, themselves, were 90cm wide and made of bricks. Between them, 2 m high *pitos,* partly buried into the ground were placed. On the south side of the granary there was a long porch, as wide as the naves of the storage, separated from the courtyard with a row of 12 square brick posts. At each of ends there were two linked square rooms. Many remains of large stone columns and bases were found in this area of the granary.

Built in the second building phase and completely separated from the main granary space, a group of six

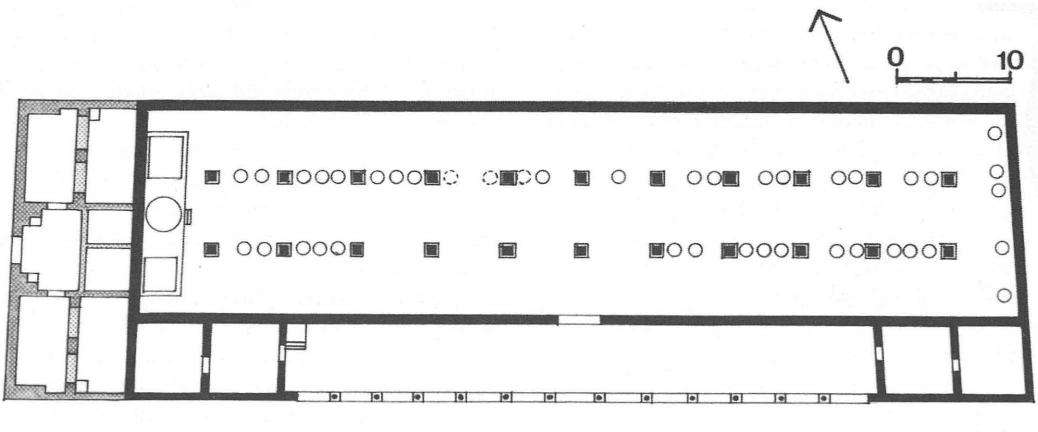

Figure 4
Plan of the *horreum*

rooms on the west side of the building, represented a part of the *horreum* that hosted the administration responsible for the collection of taxes and distribution of grain. Remains of two sacrificial altars were found in this part of the building. Apart from the described western part of the building, stone staircase in the west side of the porch, leading to the unknown position of the upper part of the building, is also considered as a part of the second building phase. The last building phase of the granary is recognized by several building activities, such as were closing some openings in the western, administrative part, and digging three pits in the main storage space of the granary.

Applied materials and building techniques

Scarce remains of the walls of the building had an average height of about 50cm. The walls were built in two different widths: 90cm for the perimetric walls, and 60cm for the partition walls. They were built mainly with partly dressed unequal blocks of red and white stone, with a sporadic use of bricks on some typical positions. The brickwork was applied as the leveling layer at the bottom of the walls, but also in the corners, doorways and crossing of the walls. The identified sizes of applied bricks were 42,5 × 27,5 × 5 cm and 40 × 28 × 6 cm, or in the parts belonging to the second building phase, 43 × 29 × 5 or 7 cm, which were formats that were typically used in this part of the Balkans in the late antiquity (Jeremiæ 1997; Radivojeviæ 2000).

The principle that was used in the building process was that larger stone blocks formed faces of the walls, while the inner space, or core, was filled with the so-called mortared rubble, consisted mostly of larger round and other pebbles (Ward-Perkins 1958). The applied binder was the lime mortar, which was poured over it, while in the brickwork parts it created thick mortar joints, sometimes even thicker than bricks. This building technique, often described as *Byzantine opus mixtum* was typical for the time of late antiquity in the Eastern provinces (Èanak-Mediæ 1980). Since *Naissus* belonged to this particular region, the use of this building technique in the case of the granary was not unexpected. However, what could be considered specific is the expressed polychromy of the walls that, according to the incised mortar joints, must have been visible in their final appearance (Mango 1976). The assumed colorfull façade of the building is in accordance with the esthetical principles of that time which often used different multicolored effects.

Walls from the younger building phases slightly differed from those from the first one. One of the differences was related to te quality of the mortar, which in later phases contained crushed brick. On the other hand, the walls were probably completely plastered. Excavations revealed that the walls from the last building phase, in fact parts of them that were filling the previous openings, did not have any foundations, but were laying directly on the soil.

Posts for the pillars or the central storage room were one of the rare examples of structures from this region that were made of cut stones, in the manner of *opus quadratum*. While in this case only the upper parts of the pillars were made of bricks, pillars of the porch were built in total only with bricks.

Foundations of the walls were built in the same manner as the walls that they were carrying. They were wider than walls up to 30 cm. According to their depth, different building phases could have been distinguishe since foundation from the younger building phases were not as deep as those of the first one, or, as previoulsy described, they were even missing.

Floors ot this building were preserved only in a form of traces of substructures or pieces of mortar layer which was not possible to be distinguished as a final layer or a part of floor substructure. It should be stressed that mortar layer from the main storage room contained crushed brick. Having in mind that this kind of mortar had hydraulic properties its application in the area where foor and other goods were stored has a logical connotation.

Parts of stone collumns and bases, as well as other elements of architectural decoration, mostly found in the western part of the building, implicate the significance of the granary which must have been carefully decorated.

Upper parts of the building could only be a matter of hypothesis. Parts of carbonized wooden structure and metal cramps indicate the possible wooden roof structure, but they could have also belonged to the kind of the lifted floor that probably existed in the storage space. Traces of ancient roof tiles, the so called *tegulae* and *imbices*, were found in the soil

during the excavations, indicating the way the roof was covered.

Reconstruction of typical structural elements of the *horreum*

Although, due to the state of preservation, our exact knowledge about the volume of the granary building is very poor, there are enough elements for different hypothesis about it. The key for any of possible assumptions is the fact that the skeleton of the building was the three-nave storage room with a porch on one of its longitudinal sides. Later extensions on the west side must have been incorporated into the original building appearance. Therefore the discussion about the reconstruction of the granary could be focused to the solution of the possible cross-sections of the original building.

Being specific by its function and size, and offering some *in situ* findings of large containers in a form of *pitos*, the manipulation of goods and reconstruction of necessary structures for this purpose deserved to be carefully thought. The input given by the disposition of structural elements was such that the central nave was bordered with parallel rows of brick pillars, laying on their wider stone posts, forming a square with a 6,5 m side. Between these pillars, three large *pitos* were placed, partly burried into the ground. Their use as containers for some goods must have required a lifted floor, that could have provided an easy access for their filling or emptying. Although indicating the roof structure in the first place, traces of wooden structures could have also be thought as remains of the former lifted floor. Since there were no traces of any separate structure that could have been used for this purpose, the idea was that some elements of the main structure must have been used for the erection of the lifted wooden floor, and the widenings of the pillars could have been used for the position of the wooden beams. These beams muste have been used as a support for the system of secondary wooden beams that were posed in the opposite direction. This row of beams could have been used as the substructure of the wooden floor, made of thick planks. According to the span of different elements of the reconstructed wooden structure, the total thickness of the lifted structure must have been about 60cm. Having in mind that stone posts were about 50cm high from the ground and that 2m heigh *pitos* were buried almost up to the half of their height, the thickness of the described structure reaches the top of the ceramic containers which could have offered an easy manipulation.

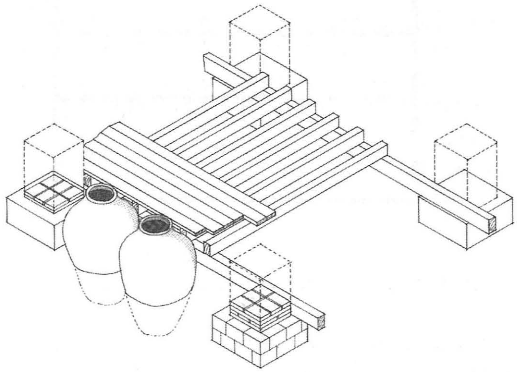

Figure 5
Reconstruction of the lifted wooden floor of *horreum*

The analysis of the geometrical characteristics of the main building part show the system of vertical structural elements, walls and pillars, that divided the storage room into three almost equal naves of approximatelly 6,5 m width. The porch that was along the south side of the building was 7,5 m wide, which was slightly, but not significantly, wider from the naves. These facts together with traces of wooden and metal elements that once belonged to a certain wooden structure, offer enough elements for possible reconstructions of the volume of the granary.

In the process of the reconstruction of the volume, some analogiees were investigated, so the similar examples of huge late antique granaries that could be compared with the analysed one from *Mediana* were found in Trier and Veldidena, Figure 5 (Rickman 1971). The one in Trier even had similar spans and widths of walls and pillars, but also the similar applied building technique. The significant difference in comparison with the *Mediana*'s granary was the existance of pilasters along the external walls of the granary in Trier, which could be understood as indicators of the former system of cross vaults that might have been applied in this particular case. On

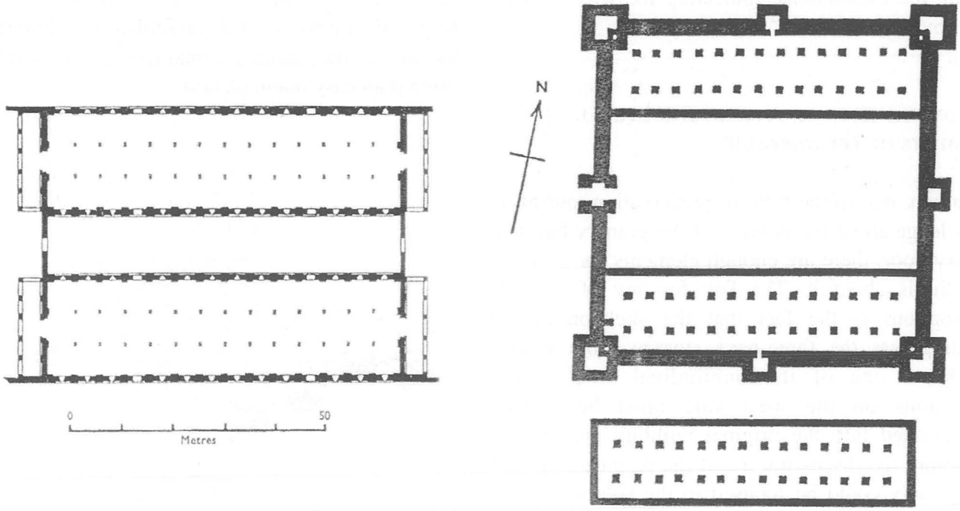

Figure 6
Plans of granaries in Trier (left) and Veldidena (right)

the other hand, the lack of such structural elements in case of the analysed *horreum* confirms that the idea of the wooden roof structure could be more probable solution for its upper zone.

Discussion about the possible volume of the granary and the disposition and form of its wooden elements is basically oriented in two directions and possibilities, Figure 6:

a) symetrical roof over the whole building, which means the storage room plus the porch, or
b) symetrical roof over the storage room, with variations in the porch that include either the possibility of extension of one of the existing roof sides, or a separate roof above it.

The roof structure itself is in all cases considered as a simple roof truss which was an invention of the Roman architecture, but at the same time, a type of structure that was extensively used in late antiquity. The massiveness of the pillars indicates the possibility that they were bonded in the upper zone with a system or arches which could have further been used as supports for the roof trusses. Possible position of the gallery, which is assumed due to the existance of the staircase in one of the corners of the porch, could be expected in the south nave of the storage room.

However, having in mind the wholeness of and symetry of the plan of the main part of the granary, represented in the storage room, we could assume that the second solution for the reconstruction of the granary's volume is the more probable one, no matter of the possible further variations regarding the porch roof.

Concluding remarks

The huge granary building from *Mediana* must have been impressive by its size, which implicates and stresses both the significance of the building itself, as well as the one of the urban settlement. This late antique building was unique in the region, and therefore it could be considered as a place of the regional interest, but it should be stressed that similar buildings existed at the same time in other regions of the Empire. Regarding the building materials, techniques and structures that were identified or reconstructed, the analyzed *horreum* was built in the usual manner of late antiquity. This means the prevalent use of the local building material, represented in rectangular bricks and local partly dressed stone, bonded with lime mortar or mortar with

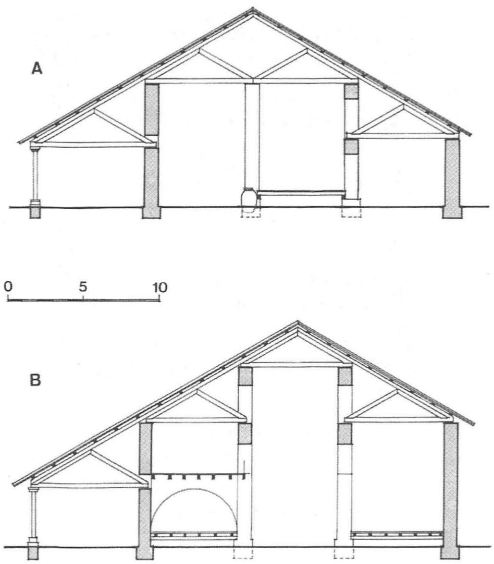

Figure 7
Possible ideal-reconstructions of the cross section of the granary

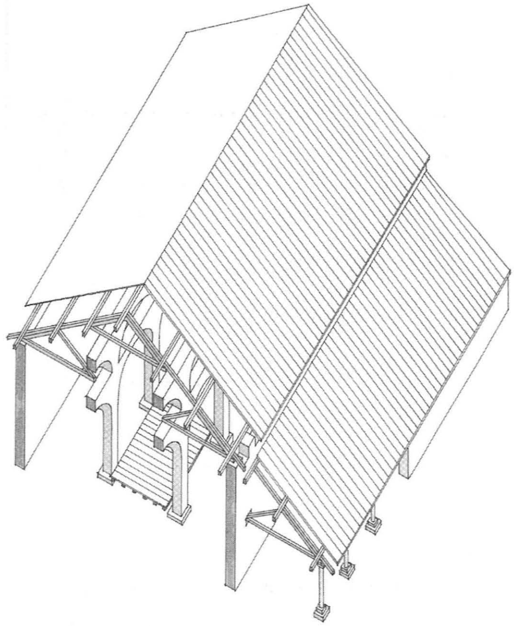

Figure 8
Isometric view of one of the possible ideal-reconstructions of the *horreum* of *Mediana*

the crushed brick. The building techniques were typical for the eastern parts of the Roman Empire to which this region geographically and administratively belonged. The assumed roof structure was also in accordance to the knowledge and building skill of that time. At the end it could be concluded that the horreum from Mediana, preserved in the total of its area, together with some interesting elements releted to its fundtion, such as large *pitos* and pits, could be considered as a good example of the late antique buildings of this region, as well as in general.

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History and construction of the Old Vistula Bridges in Tczew

Wieland Ramm

The small city Tczew (German name: Dirschau) is situated about 30 km south of Gdańsk on the western banks of the river Vistula. Here remarkable parts of the Old Vistula Bridge which was constructed from 1851 – 1857 for the so-called Prussian Eastern Railway from Berlin to Koenigsberg still exist, Figure 1.

This bridge was a true milestone in the development of civil engineering and was recognised by the engineering community of that time. Still, in the 19th Century the increasing railway traffic made the construction of a second parallel bridge necessary. When in the early morning of the 1st of September 1939 the German attack on Poland took place, both bridges were partially blown up. So today the three remaining original spans of the old bridge portray a unique historical monument of the beginning of the Second World War.

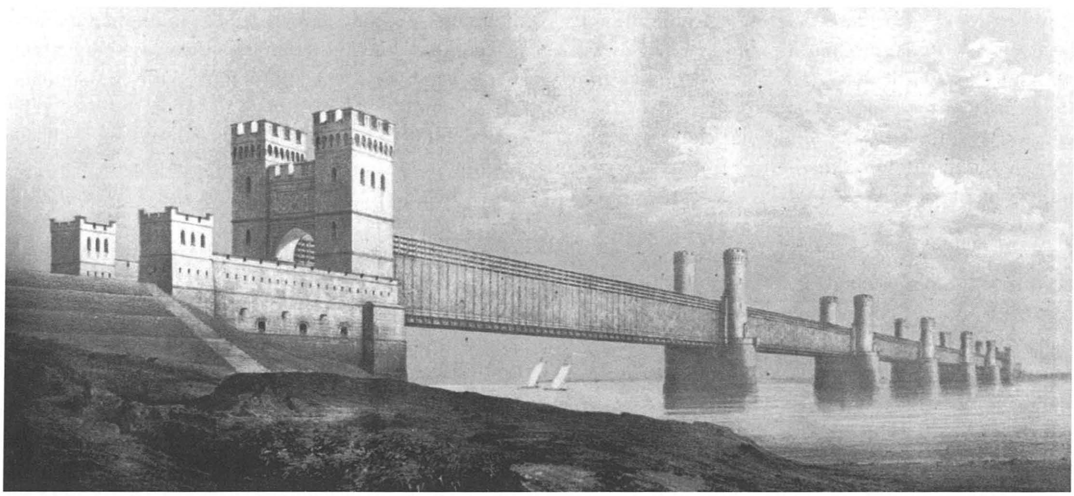

Figure 1
Lithography of the Old Vistula Bridges in Tczew (Lentze 1855)

Early Building History

To understand the technical importance of the Old Vistula Bridge it is necessary to remember the long development of building history before.

For thousands of years earth, wood and stone were the building materials available, and only the stone buildings were durable. Looking at the Egyptian and Greek temples we find very simple structures: Enormous stone cylinders placed on one another to form massive columns, topped by stone beams allowing only small spans. The Romans were, as is well known, the first great masters of arch and vault building and by this they succeeded in bridging larger spans.

We like to call the Roman master builders Roman Engineers. However we must remind ourselves that the structural systems of their impressive buildings were derived from experience, obtained by success and failure.

As is well known, the art of vault-building was refined in the Gothic Age. The bold and filigree structures of the great cathedrals can hardly be surpassed. Finally, the cupolas of the Renaissance have to be mentioned, which are quite impressive: So the cupola of the cathedral in Florence from 1420, which was designed and built by Brunelleschi. And the design and construction of the Cupola of St. Peter's was carried out in Rome at the end of the 16th Century by Michelangelo and della Porta.

When looking at these magnificent buildings it is hard for us to imagine that the builders had to work without a scientific basis all through the centuries. Construction took place only on the basis of the empirical knowledge of craftsmen and traditional experience, won by trial and error. This is proven by numerous collapses.

Ignoring early scientific research results

Nothing changed in this construction practice up to the beginning of the 19th Century. This is actually quite astonishing, as since the Renaissance, questions concerning structural statics were dealt with by the arising natural sciences piece by piece. No one less than Galilei made a start with his famous deliberations on the ultimate strength of a bending beam. Those who looked into such questions in the following 150 years, such as Hooke, Leibniz, Bernoulli and Euler, were not builders, but mathematicians and physicists. Their motivation was scientific curiousity, but not the desire to open new doors for the builders. For example, Euler sought a field of use for his mathematics when he investigated deflection curves and the buckling of members. Although the results were published, the builders of the time took no notice, or even declined to use such methods in practical constructing.

Informative in this light are the statements passed down in connection with the reinforcement of the Cupola of St. Peter's. The dome increasingly obtained cracks in the first half of the 18th Century, due to faults in the structural statics. Pope Benedict XIV was concerned and called for expert reports from three mathematicians, monks in Rome (Le Seur, Jaquier and Boscovich 1743), and from Giovanni Poleni, a professor of mathematics in Padua and on the side a hydraulic engineer of the republic of Venice (Poleni 1748). The three mathematicians wrote in their expert report: „We may be obliged to excuse ourselves to the many who not only prefer experience to theory, but also think the former alone to be necessary and appropriate, and hold the latter possibly even for dangerous.«

A person remaining anonymous reasoned: „If the Cupola of St. Peter's could be built without mathematics and moreover without the mechanics so popular in our time, then it should be possible to repair it without the help of mathematics and mechanics . . . Michelangelo knew nothing about mathematics and was still able to build the cupola.« This seemingly narrow-minded opinion can be explained by the fact that the builders had no scientifically sound education up until then.

The very beginning of Structural Engineering

A significant change only came around when the advancing development of the ecomomy demanded a better infrastructure, i.e. better roads. One requirement for this were well educated engineers. In 1747 the «École des ponts et chaussées» was already founded in Paris. Navier, who emerged from this school and later taught there, systematically collected the up until then scattered knowledge of statics and developed it further.

Parallel to this development of theory, there was a second impulse for the creation of structural engineering: In the second half of the 18th Century iron became available in larger quantities and therefore as a new material alongside the traditional building materials.

It began with cast iron, which could only be used for compressed members in structures, for columns in buildings and for arch-like structures in bridges. The latter, such as the well-known Coalbrookdale Bridge from 1779, first were orientated in their conception on stone bridges built up to then. Soon however, forgeable iron which could also be used for members under tension was produced using the puddle method, which was invented 1784 in Great Britain by Henry Cort. It therefore became possible to construct large bridges of a whole new dimension in the form of suspension bridges. Notable examples are the chain-bridges built in Wales by Thomas Telford in 1826 over the Menai Strait with a span of 176 m and over the Conway. The new order of magnitude of these bridges required a careful engineer-like work-through of the construction design and the utilization of material. At the same time the construction of cable-stayed bridges took place in the USA and on the continent.

The development obtained another strong impulse due to the arisal of the railway and the rapid expansion of the rail network in the middle of the 19th Century. Many bridges had to be built, including several which had gigantic proportions for that time. They not only had to carry large loads, but also had to be rigid enough at the same time to avoid larger deformations.

A milestone of technical progress was the Britannia Bridge in Wales, which was completed in 1850 and built under the direction of Robert Stephenson, Figure 2. For the first time an iron beam bridge which spanned 140 m was designed. This bridge and a similar, but smaller one at Conway Castle, were called tubular bridges. They had a closed box-girder section and formed a tunnel for the trains passing through. The webs, the bridge deck and the roof of the cross section were rivited together from relatively small plates and L-shaped sections, the only material available at that time. The bridge deck and the roof had a cellular structure and the high and thin walls were stiffened by vertical ribs made of L-shaped sections to avoid buckling. The pillars, which were built above the level of the beam, show that Stephenson intended to reinforce the structure with suspension chains had it turned out not to have enough load-bearing capacity, which was not the case. The success of the project required an extensive testing programm, which was carried out with scientific precision.

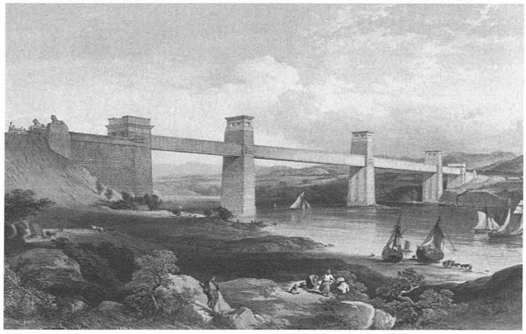

Figure 2
Britannia Bridge over the Strait of Menai in Wales, built 1846–50 by Robert Stephenson (1803–1859)

Planning and design of the Old Tczew Bridge

Directly after the Britannia Bridge, the Vistula Bridge at the city of Tczew (Dirschau) was built from 1850 to 1857 in the course of the Eastern Prussian Railway from Berlin to Koenigsberg.

The route of the railway planned after 1840 runs right through the Vistula Delta, Figure 3. Two bridges that were extraordinary for their time became necessary: one to cross the actual Vistula in Tczew and a shorter bridge to cross the Nogat at Malbork. Because of regular flooding and especially due to drifting ice in winter, bridges with large spans were necessary to reduce the clear opening as little as possible.

The construction of the Eastern Railway was carried out by the Prussian State under its own direction, and the management of the bridge projects was handed over to a high-ranking ministerial official, Senior Government Building Officer Carl Lentze. Lentze planned at first the construction of a chain suspension bridge similar to

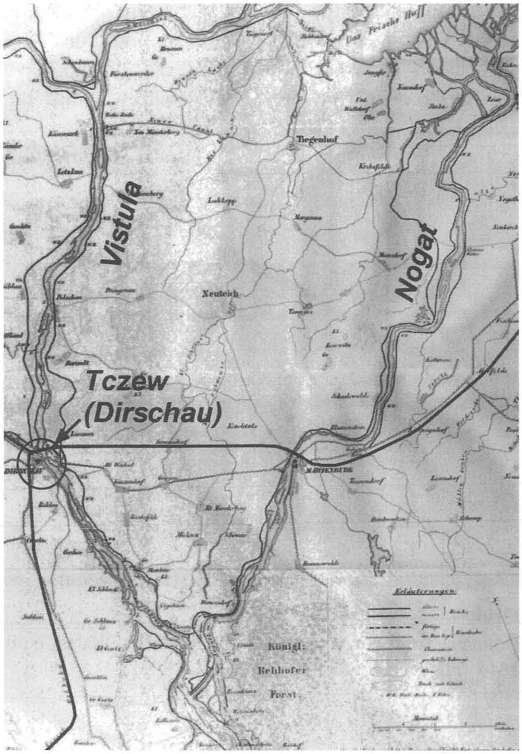

Figure 3
Map of the Vistula Delta with the route of the Prussian Eastern Railway

in 1850, was as already mentioned a so-called tubular bridge with a cross section of box girders with solid webs, Lentze chose a non-solid superstructure of fine-meshed lattices for the bridges of the Eastern Railway, using six spans in Tczew, each 131 m long, Figure 1. His inspection of the site of the Royal Canal Bridge of the railway from Dublin to Belfast when it was under construction may have played a role in his decision, Figure 4. However this lattice bridge in Ireland, which was completed in 1845, only had a span of 43 m and was constructed differently, which led to some damage (Pollack 1848).

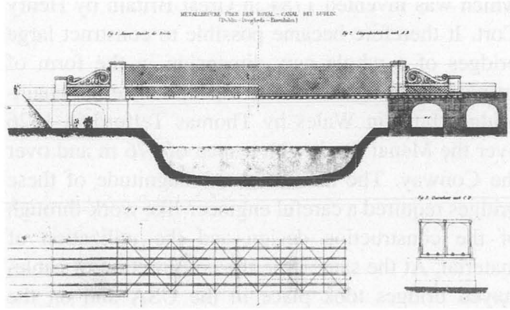

Figure 4
Royal Canal Bridge of the Railway from Dublin to Belfast in Ireland

the one he had learned of on the occasion of an information trip to Great Britain, where he visited the bridge built by Thomas Telford over the Menai Straits in 1826.

Soon after starting, construction work at Tczew had to be stopped again in 1847, due to financial difficulties of the State and to unrest leading up to the year of revolution in 1848. Carl Lentze used the time during the break in construction work to undertake a second informative trip to Great Britain, where he in particular visited the site of the Britannia Bridge in Wales and intensively studied this project of Robert Stephenson.

After his return, Lentze abandoned the project with the chain suspension bridge and decided to build beam bridges in Tczew and Malbork as well. Whereas the Britannia Bridge, which was completed

This Irish bridge was built similar to American wooden lattice bridges. When Culmanns travel report on the construction of the wooden bridges in the United States was published in Europe in 1851, it may have been a confirmation for Lentze of the decision he made.

Figure 5 shows the layout map of the Tczew Bridge with the adjacent railway routes. To reduce the length of bridge necessary, the clear opening for flooding was reduced in the eastern flooding area by new dikes.

The statical analysis and the construction detailing was carried out by Eduard Schinz, an exceedingly capable engineer, born in Switzerland. Schinz died during construction, was buried in Tczew and received a grave monument made of granite from the government in appreciation of his achievement.

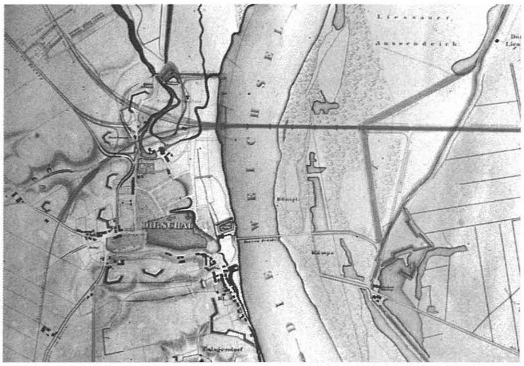

Figure 5
Layout map of the Old Vistula Bridge in Tczew

Figure 6 shows two cross sections of the old bridge: In the left half a cross section over the supports and in the right half a span cross section. A footway was placed on 1 m wide outriggers on each side. Lentze and Schinz constructed the upper and lower girders as so-called «open-celled booms» consisting of angle bars and horizontal and vertical rolled plates rivited together. The finely meshed lattice-work can be found between these two chords.

Lentze and Schinz realized that the area around the intermediate support of the two-span beam called for special constructive measures. All the cross sections were chosen proportional to their load according to the theory of Carl Culmann and Johann Wilhelm Schwedler. Therefore they reinforced the upper chord by using wider chord plates. The lower chord was reinforced near the support by using additional levels of chord plates in a stepped form to adapt it to the increased load. The dimensions of the lattice bars increases from the middle of the spans towards the supports. The vertical angle bars are chosen according to the variable shear force, so that the distance from bar to bar decreases towards the supports. They stiffen the 11,82 meters high lattice walls and prevent the bars from buckling.

Lattice-like cross beams on the bottom side and sectionalized cross braces on the upper side additionally join both the main beams. Three horizontal planes of wind braces are additionally used: one on the bottom level of the lower boom and one each on the top and bottom level of the upper boom, Figure 6.

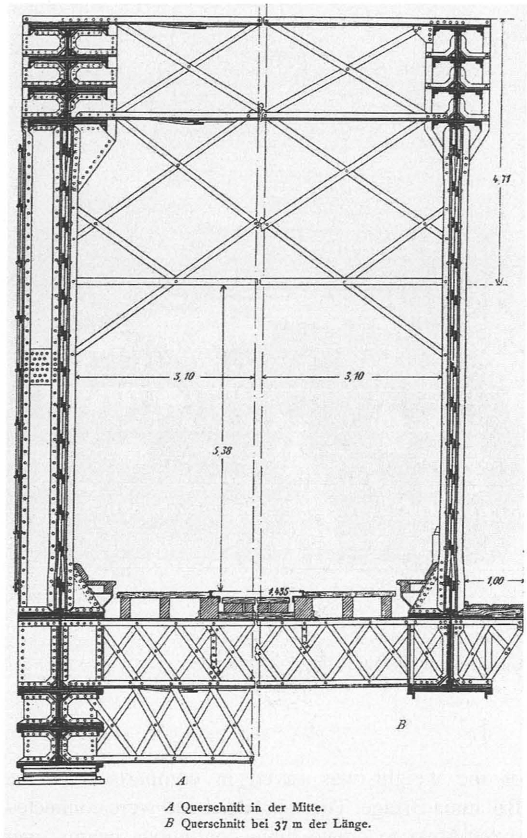

Figure 6
Cross section of the Old Dirschau Bridge. In the left a half cross section over the supports and in the right half a span cross section, the latter 37 meters away from the support.

Construction of the Old Tczew Bridge

In 1851 the ceremonial laying of the cornerstone by the Prussian King took place at the abutment on the Tczew side, Figure 7. Construction went by plan, and the bridge could be opened for traffic in 1857.

Although the construction of the old Vistula Bridge was carried out by the Prussian government, it was incorporated in the international development of bridge construction and is counted as a true milestone of structural engineering, Figure 8.

By the chosen system with finely-meshed lattice-work, in spite of having almost the same span, a third

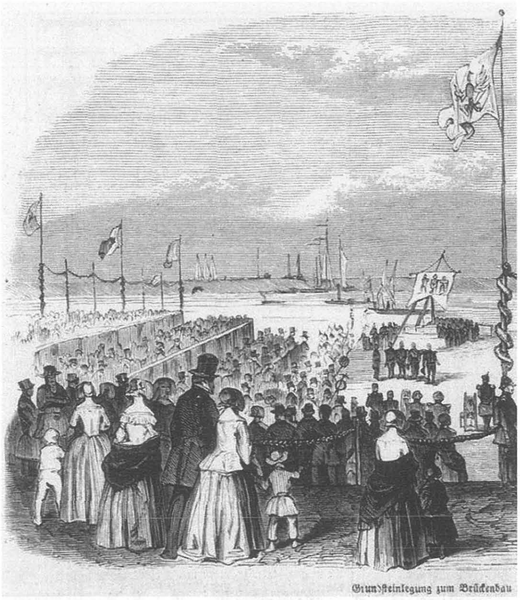

Figure 7
Ceremonial laying of the cornerstone

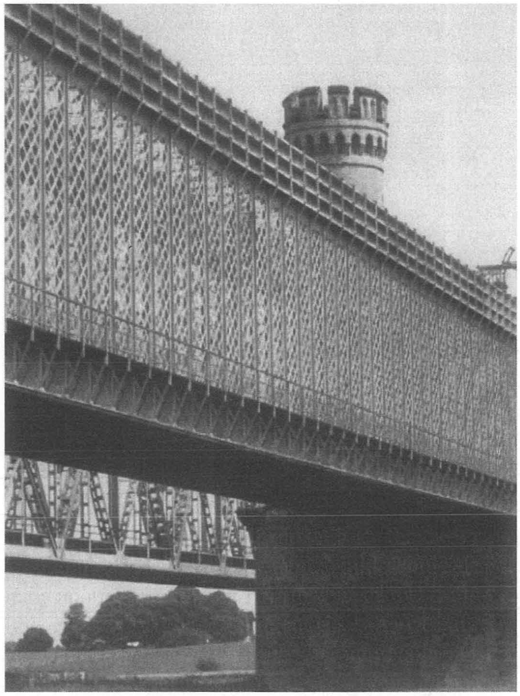

Figure 8
View from the south-west with two spans of the remaining old bridge from 1857 in the foreground and the extension from 1912 in the rear.

of the weight was saved in comparison to the Britannia Bridge. The six spans in all were connected two-by-two to create three continuous beams over two spans.

Therefore this pioneer achievement became a model for a large number of big and small bridge constructions in Europe. Here only the first railway bridge over the Rhine at Cologne shall be mentioned. It was completed in 1859, two years after the bridge at Tczew, and only had a span of 105 m.

Further development up to the Second World War

The view of the portal of the old Tczew Bridge, Figure 9, shows that the bridge was for both railway and road traffic with horse-drawn carriages. The railway track was embedded in a wooden carriageway made of planks.

Of course before each train passed, the bridge had to be closed to road traffic in time. In the following decades the amount of railway traffic, which was

Figure 9
Portal of the old Tczew Bridge

sparse at the beginning, increased rapidly, and so gradually caused intolerable conditions for road traffic. Consequently, it was decided to erect a second bridge, which was built from 1888–1891 as a two-track railway bridge for rail traffic alone, 40 m away from the old bridge which from then on served only for road traffic. In order not to additionally disturb the clear section of the Vistula, the new bridge obtained piers in the same position as the old bridge. Large fish-belly girders were chosen for the six spans, Figure 10 (Goering 1890).

When the danger of a German invasion of Poland grew in the summer of 1939, the Polish army prepared to blow up both bridges as a measure of defense, which became known to the German side. When the German attack on Poland began in the early morning hours of the 1st of September 1939, the German „Wehrmacht», i.e. the German Army, tried to take over the bridges undamaged in a surprise attack. This action failed, the bridges were blown up after several battles, and three spans of each of the bridges from 1857 and 1891 were lost, Figure 11.

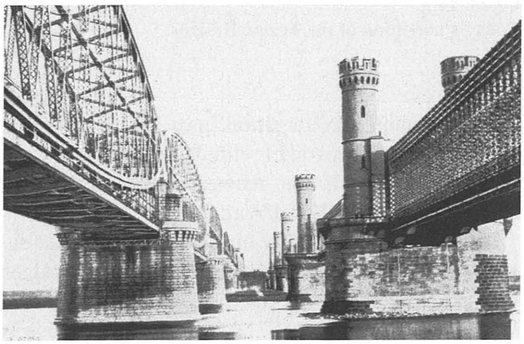

Figure 10
Second railway bridge at Tczew (left) together with the old one (right)

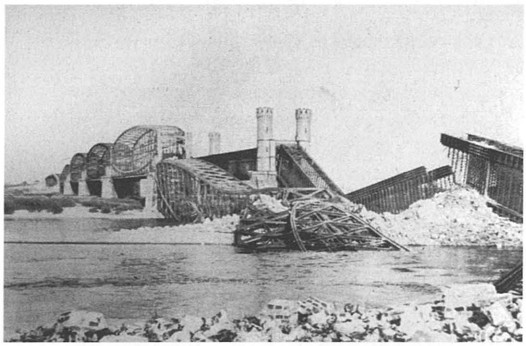

Figure 11
Blown up spans at the beginning of the Second World War

At the beginning of the20th century, heavy flooding forced new measures to be taken to regulate the flow of the Vistula and the Nogat. The artificial measures which had been taken to narrow the Vistula at Tczew were removed again. As a result both bridges had to be extended at this place by about 250 m, which was done from 1910–1912 by erecting three additional spans with simple parallel-chorded trusses, Figure 8.

Events at the beginning of and during the Second World War

In this prolonged configuration the bridges survived the time up to the Second World War. Since the end of the First World War, the bridges belonged to Poland and the region of the Vistula Delta belonged to the Free City of Gdańsk.

During the war the German side supplemented the railway bridge in only a few weeks with an auxiliary bridge which was turned out of the longitudinal axis of the railway bridge, Figure 12.

This auxiliary bridge was replaced by a permanent construction in the axis of the railway bridge within one year. The old bridge remained as a rudiment. It was only used as a pedestrian bridge and was for this purpose connected at its end by a foot bridge to the railway bridge, Figure 13.

At the end of the Second World War the railway bridge was blown up once again, this time by the Germans.

Final Remarks

The Polish reconstruction after the war led in single steps to the current condition, Figure 14, which now

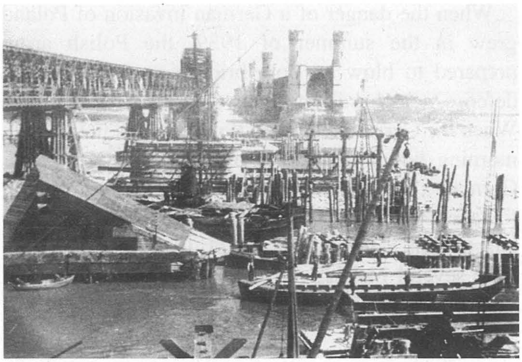

Figure 12
Auxiliary bridge built in 1939 by the German Army

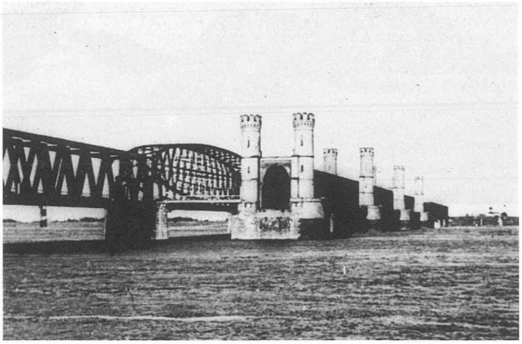

Figure 13
The Tczew Bridges during the Second World War

consists of many different parts from which its turbulent fate can be read.

In the foreground of Figure 14 the row of spans of the old bridge can be seen. It begins on the left with two spans over the Vistula River, which today consist of girders from the British military system developed by Bailey.

The next three spans are the original parts from 1857. Further to the right there are small trusses, replacing the destroyed sixth span of the old bridge. At the right end, three spans from the prolongation of 1912 can be seen.

Behind the old bridge, Figure 14 shows the railway bridge constructed later. No parts of the original bridge from 1891 exist today. At the right end a part

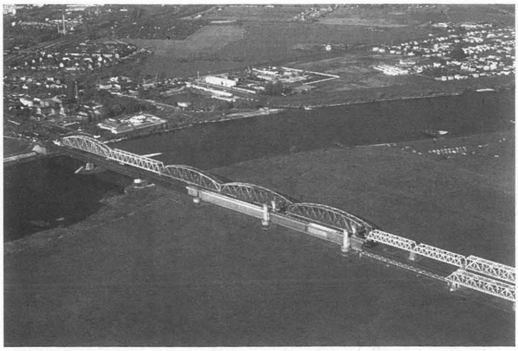

Figure 14
Today's condition of the Tczew Bridges

of the remaining prolongation from 1912 can still be seen. The other parallel chorded trusses are the remaining parts of the reconstruction work done during the Second World War.

The research of military history has shown that the start of the German action against the Tczew bridges was possibly the very first fighting of the Second World War (Schindler 1971). Therefore the bridge is also a memorial of the younger European history, which reminds us of the beginning of that terrible war.

Above that, the three spans of the old Vistula Bridge from 1857 which remain in their original state, Figure 15, portray a truly unique technical monument of early structural engineering, after the Britannia Bridge in Wales has been replaced in recent times. It should be the unconditional European task to support Poland in preserving the building substance of this exceptional legacy.

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Figure 15
One of the remaining spans of the Old Tczew Bridge from 1857

Le Seur; Jaquie and Boscovich. 1743. *Parere di tre mattematici sopra i danni che di sono trovati nella Cupola di S. Pietro sul fine dell'Anno 1742.*

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The work of Alessandro Antonelli[1] and Crescentino Caselli[2] between the Architecture of the *Raison* and the *architecture raisonnée*

Luciano Re

The representation of the Mole Antonelliana on Italian 2 cents coins recognizes this unusual modern monument as the symbol of Turin, but at the same time confirms its conventional image: the sharp profile that towers over the neighbouring houses roofs does not reveal its identity, constituted of little matter and of strong constructive conception, nor its proportions and its neoclassic style as a solid dignified appearance, contrast to the changing suggestions of the Eclectic taste. The Mole dominates Turin (figure 1), however it is placed in an recent anonymous building plot aside its ancient core, and it reports to the urban development rather than to its built surroundings: likewise the *Sagrada familia* in Barcelona. As for that, the attention of the critics regarded more its exceptionality, then its relationships with the town and with the history.

The Mole,[3] 167 meters high and in origin all in brick and stoneashlar masonry with same necessary iron tie beams, has been understood as «a monument to the megalomania of his architect» (Hitchcock 1971), comparing it to the Tour Eiffel, built during its achievement in 1888. This concept neglects however the complex relationships about Architecture/functions and traditional/innovating technologies, that characterize it. Admired, criticized, feared from the contemporaries, the Mole arouses from a century a thin and prestigious *fil rouge* of critical attention, understood to report it to the European experiences of its age and to the large and coherent context of the production of its author, distinguishing it among the buildings of the Italian Eclecticism, adressed essentially to stylistic improvements. The Mole and all the works of Antonelli report instead, more than to the Italian culture of their time, to the Illuminism's principles of the rationality in the building arts and to an acute sensibility to the tasks of the architecture in the prevailing bourgeois and liberal society: rational organisation of the cities, production of solid and dignified public and private buildings and efficient and economic houses, optimizing realistically the available local resources. A coherent program, referable to the teachings of Durand, but without rigorisms; referring to the accelerated developments of the century and to the material conditions of Piedmont at that time: good tradition of the arts, scarcity of new materials and industrial technologies. A well-tried bricks, mortars, stone architecture, as done by expert and intelligent workmen; a proper neoclassic style no more reserved to monumentals edifices but applied to all normal tasks of current building (Daverio 1980:59): a choice that reminds the Loos' judgements about the most proper dress of the modern man and the impossibility of conceiving new ornaments.

Crescentino Caselli, faithful, coherent and innovative disciple of Antonelli, affirms:

> Antonelli was the teacher to himself, and he is the just one Italian architect who, formed when all swore for Greek and Roman, was able to give to his works a very mighty

Figure 1
The Mole Antonelliana in Turin

personality, and to develop a system in architecture, I would say a style, all his own. In his system, the walls do not exist otherwise then as enclosure and shelter; the support and the solidity of the building is all delivered to pillars, that are the principal support, to arches, wich brace pillars, and give an additional support when suitable, and prop the vaults; order and equilibrium govern and harmonize all the masses. (Caselli 1889)

A century later, we may ascertain however that such prophecy as not been accomplished, because of the rapid transformation of the productive and social context: the spread of reinforced concrete technics, the reduction of the building trade to a subordinate role in the increasing industrial town,[4] the ephemeral *fin-de-siècle* fashions. So as it happened in all other fields for the utopia of Ruskin and Morris, the development of the technologies and the industrialisation, between XIXth and XXth Century, has laid in aside the optimization search of the masonry building, that Antonelli pursued with constant coherence in all his works (monumental architectures, public buildings, residences). Such building optimization concerned equally both typologies, and technologies, through the regularity of the modular plans and of the supporting framework at *fulcri* (pillars, granite or masonry columns) that hold up the thin domical vaults in bricks, that are flat layed in concentric courses stiffed by arches at the extrados. The vaults are often let very lower, like a kind of continous velarium, that favours opportunely the diffusion of daylight, allowing to realize very thick bodies of building. That technique could be applied as well to the frame of the roof, built with arches and vaults in bricks to support of the covering in tiles: as it was made by Caselli in the *Ospizio di Carità* (poor-house) of Turin[5] (figures 2, 3, 4). A few illustrations can display the singleness and the constructive and spatial values of that building method and of the brick-roof system as an alternative to the iron construction, still extraneous to a country as Piedmont, where the industrialisation was just begun and instead the resources of the traditional crafts were subject to be cleverly addressed toward the same aim. The amazing exaltation of the relationship between spaces and masses obtained in those buildings is without equals[6] except in the iron-masonry architectures, like those realized or conceived by Labrouste and Viollet-le-Duc, starting on analogous principles and aims of rationality; and likewise expressed in rigorous forms, oppositely to the new

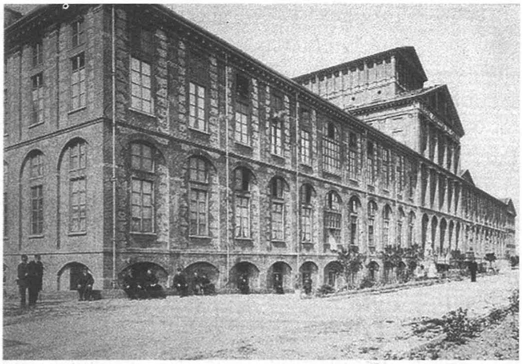

Figure 2
The Ospizio di Carità in Turin, at its achievement in 1887

Figure 3
Front wiew of a pavilion of the Ospizio di Carità

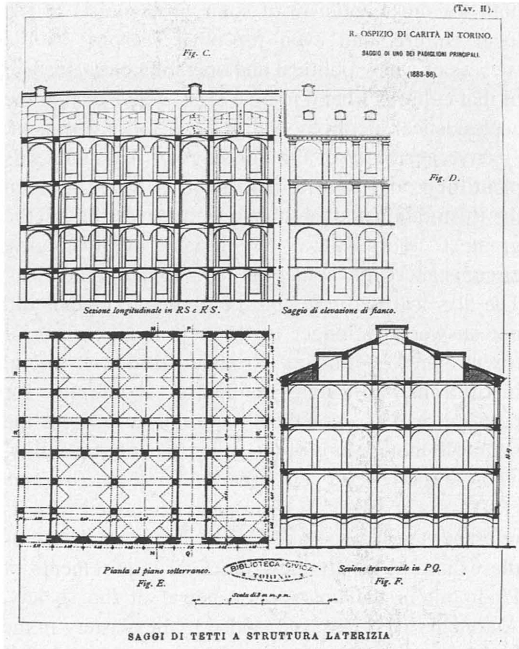

Figure 4
Cross section and perspective wiew of a pavilion of the Ospizio di Carità (Caselli 1894)

tendencies to «serving of all the concepts of the different styles in accordance with the utility, the opportunity and the taste» (Boito 1891). In the Antonelli's and Caselli's works the architecture (aimed to the new functions) and the structure (according to the scientific knowledges) are integrated in the conception and in the practice, so as it was still possible at that time, when the professional rules and technical competences were just dividing, and either an architect (as Antonelli) or an engineer (as Caselli) were both able to conceive, to proportionate and to realize completely not only usual buildings, but even the most audacious and extraordinary ones, as experimentations and demonstrations of the progress of the art.

The works of Antonelli and Caselli, realized in the course of about a century (1830–1930), bear witness tu a significant phase of the history of the Italian architecture, from Neoclassic to Modern Movement, across and against other changing experiences occurred in those times, but they are circumscribed in a part of the Piedmont, among Turin, Novara, Alessandria and their countries.[7] That undoubtedly marginalized them, in a freshly united Nation, whose capital town was transfered in a few years from Turin to Florence and finally to Rome (1870): that is those who are still the centers and the references of the Italian tradition of arts and of knowledge by the foreign connaisseurs. Moreover, the «Metodo antonelliano» does not find a generalized consent,

both for the scepticism of some protagonists of the local culture, and even for other reasons, as the success of a new political and operating class, instead of that cultured liberal middle class, active also in the ecclesiastical hierarchy and in the local government, elective appointer of the buildings of Antonelli. His plentiful production was realized in the years between the Restoration and the Italian Unity, even though the greatest works are developed in following circumstances and sometimes among hard polemics.[8] The classical tradition and the academic models did not answer any longer to the new requirements of towns and countries (roads, bridges, social institutions buildings, residential typologies for housing or rent), nor they were able to express the manifold motivations of the new romantic sensibility. The experiences of the Napoleonic years (1800–1814) and of the European new asset, with its references to France and United Kingdom, arose as the examples for the new practical requirements of Piedmont in the bourgeois renewal of the society. Antonelli, like Labrouste, added to the mastery in the neoclassic architectural composition, acquired during his studies at the academies of Milan, Turin and Rome, the new interests for the building crafts and the rationalization of typologies, as promoted by the precepts of Rondelet and Durand. The new task of the Architecture (who nothing of the civil society was extraneous, according to Ledoux) was the pursuit of the material and cultural progress, beyond the expression of consolidated values. The field of the architecture was equally open to all buildings with useful destination (as bridges, hospitals, markets, museums, theatres, schools, public gardens), conceiving the art as a «*moyen efficace de contribuer au bonheur public*», «*faisant usage . . . de la méthode que la raison indique*» (Durand 1825), in order to «*partager . . . les aisances et les commodités de la vie*» (Navier 1809). A further aim of the architecture was the one suggested by Navier: «*l'art consiste . . . à faire le moins de dépense et à employer le moins de matière qu'il est possible*» (Navier 1830). That is a concept to be applied not only in an economic value, because the architecture coming from those principles, by its characteristics of lightness and rational disposition of the materials, participates of the natural laws of symmetry and of equilibrium, «*et les caprices du goût ne pourront jamais en altérer l'élégance*» (Navier 1830). Navier was dealing with suspension bridges, but the observation can be applied to a lot of buildings from the architecture of Illuminism to the Modern Movement, from those according to Laugier's theory, to Sainte-Geneviève by Soufflot and the Bibliothèque Nationale by Labrouste, till the works of de Baudot and Séjourné.[9]

The works of Antonelli and subsequently those of Caselli, too often neglected by critics as marginal curiosities in comparison with the cultural debate of those years (the conversion, one after the other, of Turin, Florence and Rome into modern capital cities; the pursuit of a National Style, the restauration —or integration, or ideation— of the medieval and Renaissance monuments, the international Competition for the monument to celebrate the Italian Unity and its first King, Vittorio Emanuele II) appears unusual for their rational dispositions of frames and spaces, for their strict relationship between the building art and the use of the materials (from which both their design and their shapes proceed), for their wide field of interest, open to the emergent necessities of the modern society. From these assumptions, it resulted reliable and durable buildings, containing in the least volume the most useful space, well illuminated and airy; by using and encouraging the development of the best local resources: workers skill, good quality bricks, mortars, stone ashlars. Those buildings show altogether how innovation and progress descend not necessarily from the availability of new technologies and material resources (iron, pit-coal), still scarce and very expensive in Italy in those years; but from the critical intelligence in dwelling with the tradition.

As in the Durand's *Précis*, architectural typologies of Antonelli and Caselli derive from the *combinaison* of space and frame modules (the squared «*grille polytechnique*») creating regular cells, disposed both in consequence and organisation of the functional programme of the building. Synthesis of classical culture and of social intentions, this «*raison*» was able to give a progressive answer to the pursuit for the identity of the new Italian architecture, so ennobled as conditioned from the mythes of its old tradition. But already in the Competition for the Parliament Palace in Turin (1864), Antonelli's project was left behind in favour of another, whose emphasis, whose sumptuous stylistic *pastiche* of manifold inspiration, inevitably preludes to the buildings of the King Umberto I style.

The wide architectural production of Antonelli (more of 80 great buildings planned, of which more of an half

Figure 5
The reneweled Cathedral of Novara, 1864–68

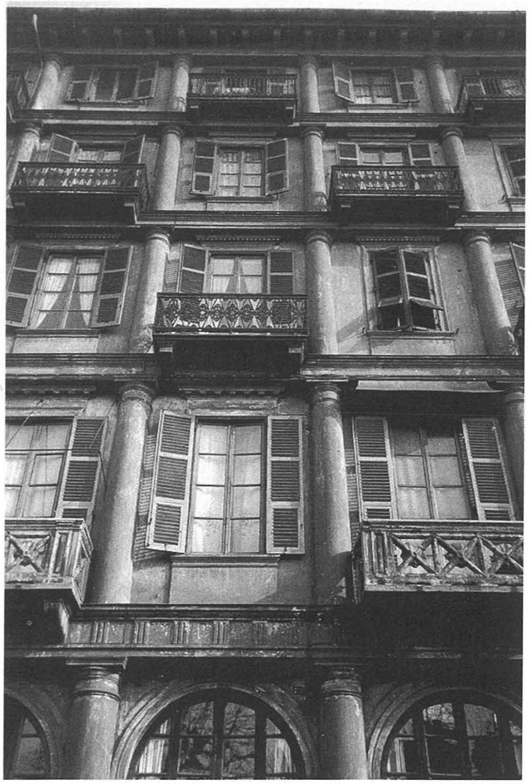

Figure 6
«Casa delle Colonne» in Turin, 1853

was realized) includes the new Cathedral of Novara (figure 5), replacing the ancient one —demolished in spite of the disapprovals by many connaisseurs of medieval art—, plans of urban development for Turin (one of which was suggesting in 1852 to build a railroad to connect the three planned railway head stations), residence buildings as growth and renewal of preexisting constructions (as it was usual) or of news and rational establishment (figure 6), many parish churches, kindergartens (figure 7), boarding schools, hospitals . . .

> Unusual then is that his projects are conceived and appointed even in the smallest details, and when they are performing, he himself is at the same time the architect, the head manager and the assistant, the builder and the bricklayer, the stonecutter and the plasterer, and the carpenter, because he is able to teach the best rules to all workers; and that same hand which still today masters so well pencils and compasses, is expert to model in clay a Corinthian capital, worth of the best sculptor. (Caselli 1884)

Crescentino Caselli production was as much plentiful, and it is placed mostly in towns and countries between Turin and Alessandria. His buildings show as still after the end of the XIXth century Antonelli's method was susceptible to the most various applications with the same dignity and quality result, even in constructions «straight microscopic for importance and dimension, however existing in various circumstances and conditions and in tight relationship with common experiences in the field of the civil architecture» (Caselli 1894). In particular, even thanks to a personal conception of the restoration —at that time a main subject of the cultural debate— (Vinardi 2000), and the comparison with the contemporaneous European experiences, Caselli proved as the new building system —non necessarily pertaining to the classical language, but by means of the sincere exposure of his constitutive elements and of the various materials (those of the tradition, which he added enameled tiles in the capitals and in the modillions and emphatized wrought iron works— gratings, railings, heads of tie beams) proposed new decorative suggestions to the

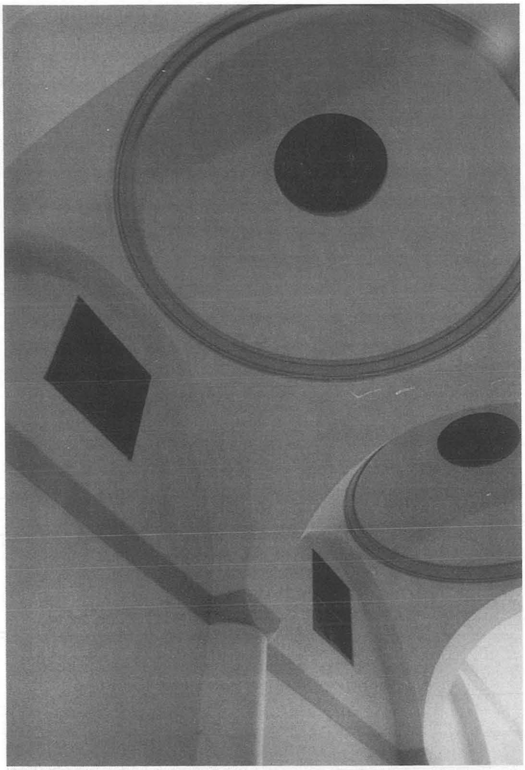

Figure 7
The Kindergarten in Bellinzago near Novara, 1873–76

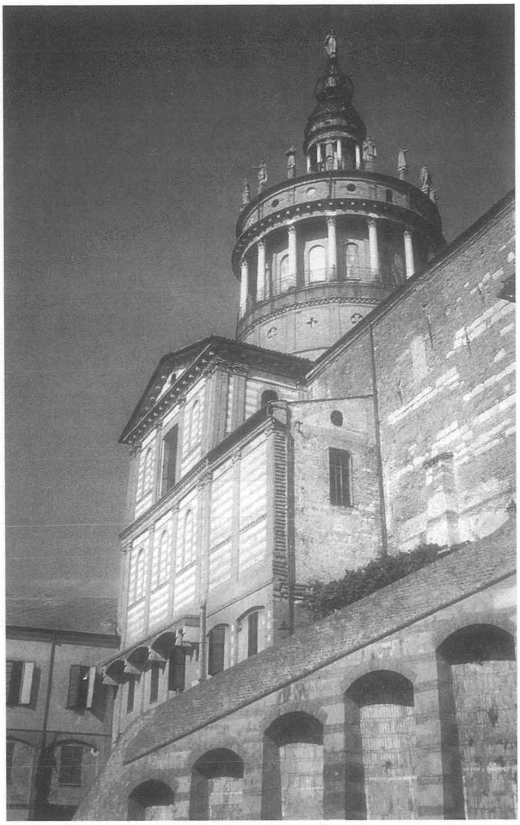

Figure 8
The Dome of the parish of Camagna near Alessandria, 1887

Eclectic taste (figure 8). Excluding any utopy of return to the past, those architectures, understood to the innovation of the art of the building arts in reponse to the modernisation of the society and of the towns, realize their relations with the tradition by innovating experiences and the exemplarity of a production, whose cultural meaning goes beyond their circumscribed geographical and chronological circumstances.

This double finality, of experiment and demonstration, sustains the highest and most audacious Antonelli's architectures —the Mole in Turin and the Dome of the San Gaudenzio Basilica in Novara— not as curiosities and eccentricities of a seclusive genius, but as a synthesis of an historical condition and proposals towards the future. The Mole, usually considereded only for its structural performance, presents about that many cues of reflection. The center for the Israelitic community of Turin, aknowledged in Piedmont's laws with the Statute of 1848, would gather in a small lot manifold available functions (temple, schools, administrative offices), in one building of strong symbolic connotation. Proposing an unitary and complex resolution to this task without preceedings, Antonelli declared his intent to add a further aim: «to give light to the progress of the masonry and stone building for the great vaults»[10] while «the more appropriate to our Italian uses, the most profitable to our cares and duties, employing preferably the materials of which the nature was lavish for us» (Figures 9, 10). The occurrences stopped the achievement of that program and the building remained incomplete, until its care was taken by the City Council. It is a point, that

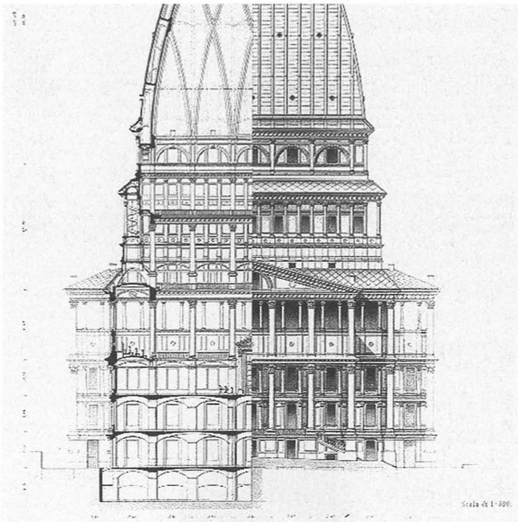

Figure 9
Mole Antonelliana; detail of the front view and cross section by Crescentino Caselli, 1872

among the lot of Synagogues of those years (including that built in Turin afterwards), only the Mole would have assured to the Community not a monument inspired by memories and recreated styles of the ancient East, but an architecture-symbol of her living presence in the contemporary society. A similar observation, even if with smaller evidence, is valid regarding the several catholic churches planned by Antonelli, without never indulging to the influence of the neo-Gothic taste, or refer to the past, till justifying the substitution of the ancient cathedral of Novara.

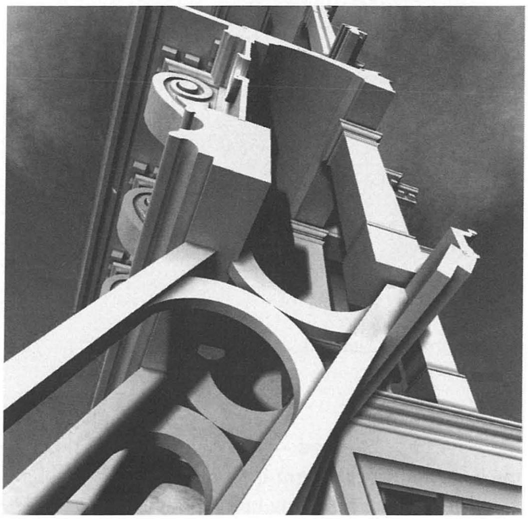

Figure 10
Mole Antonelliana; frame between the Pavilion and the «Tempietto» (rendering by F.Algostino)

Analogous considerations are also valid concerning the high Dome, that Antonelli superimposed on the preexisting San Gaudenzio Basilica at Novara (figures 11, 12). The dome, although notably lower than the Mole, is established on a such amazing structure —for complexity and lightness—, as to be valued —at least regarding the building art— as synthesis or conclusion of a secular progress of the typology, from the domes of ancients times to those by Brunelleschi and Michelangelo, and by Mansart, Wren and Soufflot (Daverio 1980). In its growing and implementing process through the following developments of the project, the Dome relates to the actuality too: the

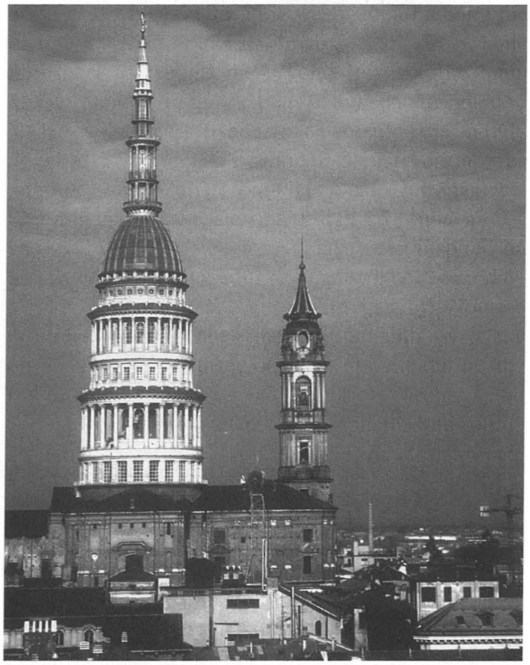

Figure 11
Dome of San Gaudenzio's Basilica in Novara

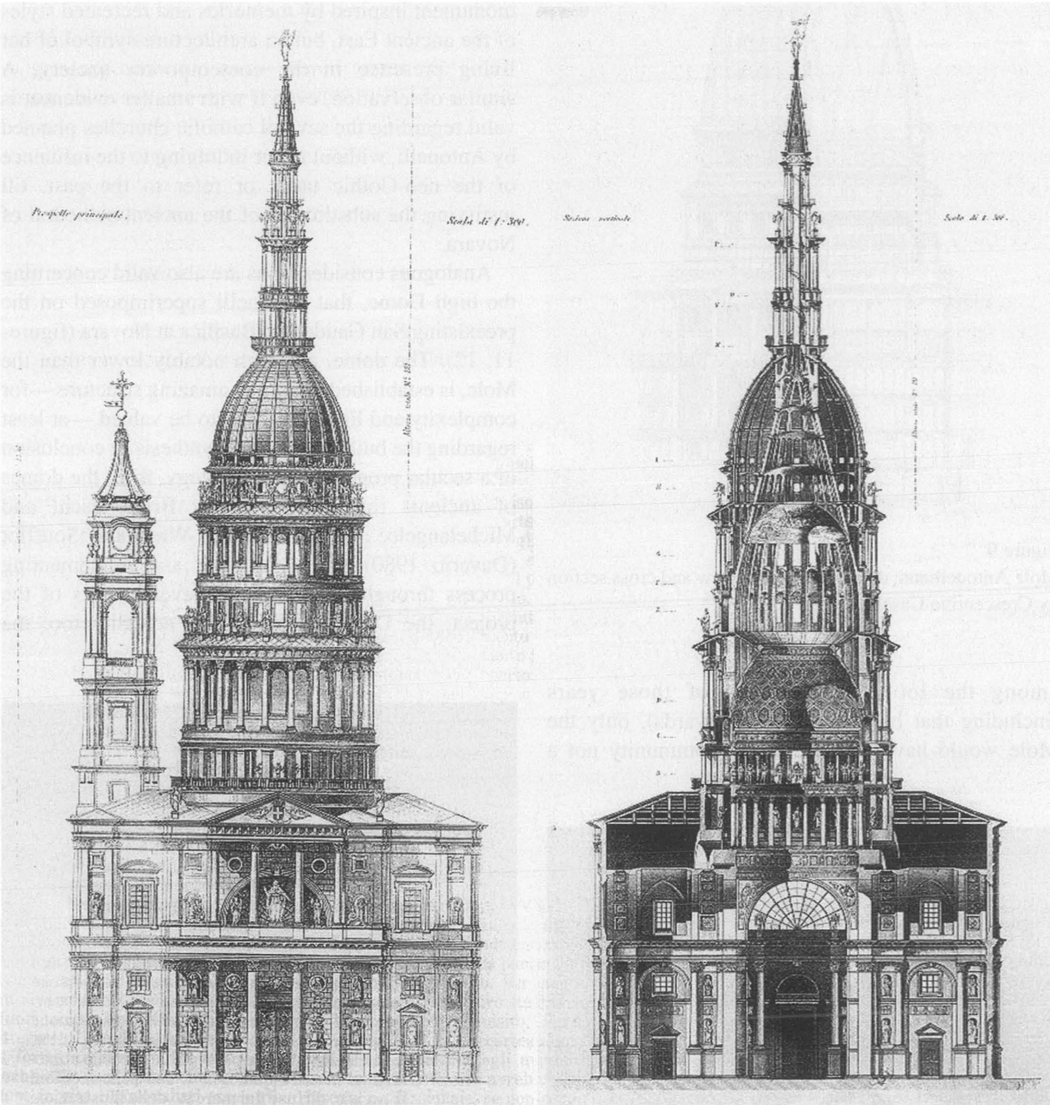

Figure 12
Dome of San Gaudenzio's Basilica in Novara; front view and cross section by Leandro Caselli, 1877

masonry cone enlighted by holes that make its space permeable to the light can be compared with the dome of Wren[11] (or the Romanesque Baptistery of Pisa), but also with contemporaneous buildings, as the towers of the suspension bridge of Cubzac. Its meaning is not only in the relationship with the underlying Basilica, that it has climbed over with the audacious interposition of a system of great parabolic masonry arches, without grounding upon the inadequate arches of the ancient transept; but the new Dome imposes its outline above all the country: «so ample to cover with its shades all the peoples», how Leon Baptist Alberti

stated about the dome of Brunelleschi (Alberti 1975).

To those accomplished buildings, that subsist though overloaded from the invading reinforcements imposed by cautions, perhaps impossible to avoid, but heavily conditioned by the methods of validation operable in the first half of the XXth Century, we could add the latest ideation, entrusted by two autographs by Antonelli, sketched with pencil in plan, cross-section and elevation, together to other drawings perhaps referring to the same object.[12] They delineates allusively a third masonry Dome, defined as a «church»; but certainly it refers to another monument, perhaps a preliminary thought on the international competition for the mausoleum of the Kings of Italy. We know indeed by Caselli that Antonelli, nearly ninety years old, was applying to that task (that hypotesis presents however some chronological discordances). The building appears covered by a titanic dome, an ogive at «tubular structure or like a beehive» (as Antonelli himself related the Mole's pavilion, interconnected by means of «right-reversed arches»), that supports a great two-level Lanterna[13] (figures 12, 13). Supposing that this building was such as to respect the Galilei's evaluations about the proportions of the frames of a giant; and that the intuition of Antonelli was able to let it safe against sismic risks and strengthes of the

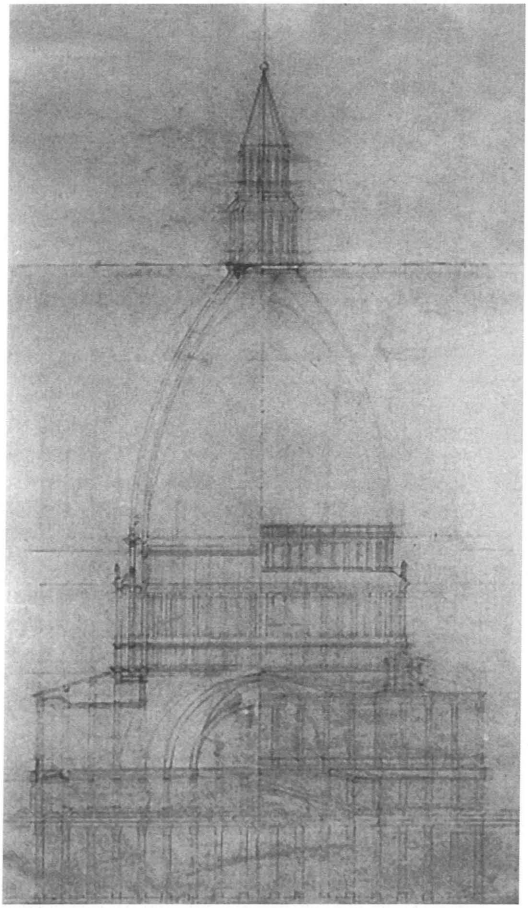

Figure 13
Cross section of the Third Dome, outlined by Antonelli (Archivio Antonelli, Galleria Civica d'Arte Moderna, Turin)

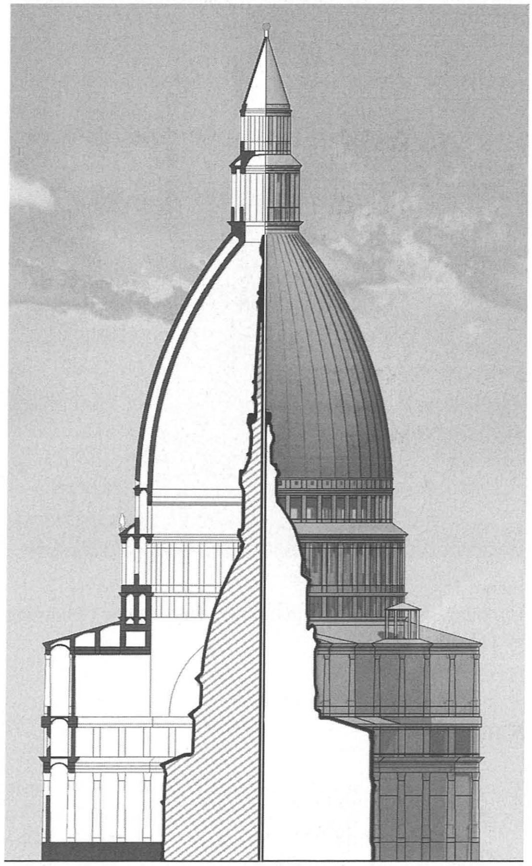

Figure 14
Comparaison between the three Domes (rendering by D.Borra)

winds, as he achieved for the Mole and the Dome; and that it was possible to carry out the works without the improvement assured by his continuous presence in yard (as a few years ago he was able to do for the Mole),[14] the steady realism that had sustained the audacious preceding monuments sublimates by now into the Utopia. A century after the achievement of the Panthéon of Paris, the «*architecture raisonnée*» seems to complete its historical experience, merging with the visions of Boullée,[15] towards the sources of the architecture of the *Raison*.

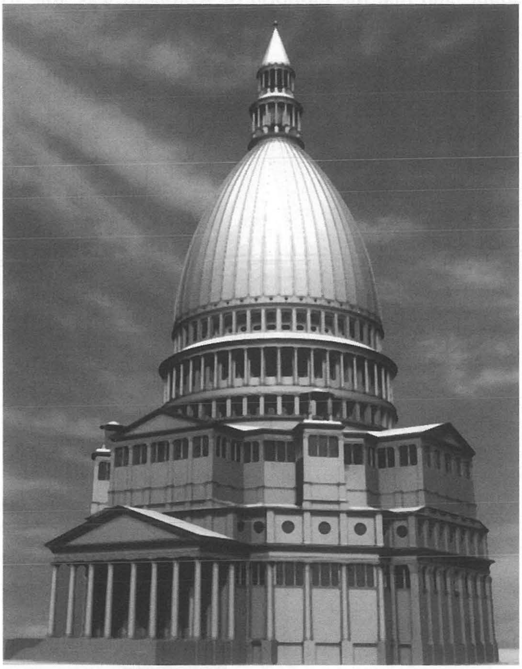

Figure 15
Hypothesis on the re-creation of the Third Dome (rendering by D.Borra)

Notes

1. Alessandro Antonelli (Ghemme, Novara, 1798–Turin 1888), architect, professor at the Accademia Albertina of Turin: Rosso 1989; Biancolini 1988 (with bibliography). Crescentino Caselli, Camillo Boito, Arialdo Daverio, Carlo Mollino, Roberto Gabetti, Franco Rosso, Vittorio Gregotti, Aldo Rossi, are among the critics who have written on Antonelli.
2. Crescentino Caselli (Fubine, Alessandria, 1849–Bagni San Giuliano, Pisa, 1932), engineer, professor at the Accademia Albertina and Politecnico of Turin: Rosso 1979.
3. The building was begun in the 1863 as synagogue. The continous development of its construction and the polemics on its stability led to the interruption of the works and to their acquisition by the Town Council of Turin, to dedicate it as the monument to the first King of Italy, Vittorio Emanuele II. Its consistence is today substantially altered from the consolidations in reinforced concrete carried out from the year 1928 and from the substitution of the pinnacle, torn from a hurricane in 1953 and reconstructed with steel frame in 1961. The interior has been recently staged to a *Museo del Cinema*.
4. The Factories FIAT were founded in 1899; when Turin, no more capital of the kingdom of Italy since 1864, had already assumed a remarkable consistence of an industrial town.
5. The Ospizio (1883–87), of a lenght of 351,50 mt and nearly 100 mt of depth, was the greatest building of Turin before the Fiat Lingotto Factory. The question of the incombustible roof, proposed in the XVIIIth Century (Espie 1754), finds references in Italy in the project of Antonelli for the theatre of Novara, 1858, and in the new Departement of the Finances building, Rome 1876, by the architect Raffaele Canevari. Caselli adopts it for his building, theorizing it in an Essay on tile structure roofs-*Saggi di tetti a struttura laterizia*, 1894; also because it makes habitable or at least usable the rooms under roof. For a systematic exposure of the building method employed by Antonelli and Caselli, see Franco Rosso (1979, 1989).
6. The relationship between the structure and the cover area of the Mole is of the 5,4%, in comparison with the 15,4% of the Panthéon of Paris (Gabetti 1962).
7. Nevertheless, some buildings by Crescentino Caselli are too in Pisa and Cagliari and others of his brother Leandro in Carrara.
8. Particularly, those about the rebuilding of the ancient cathedral of Casale, proposed by Antonelli (1853–54), and contrasted for the safeguard of historic values by Luigi Canina and Edoardo Arborio Mella (that afterwards realized its stylistic restoration); those about the ancient cathedral of Novara (where Antonelli realized his project, 1864–69) and those on the inexorable growth of the Dome at Novara (1841–64) and of the Mole at Turin (1863–88).
9. The building method proposed by Antonelli and its development in the works of Caselli could be compared to the construction and the ornamentation, not stylistic but structural, of the examples proposed by Viollet-le-Duc in the *Entretiens* and in their applications. Another

question is proposed by their suggestive space analogies and motivations (not extended at the consistences) with the *bóvedas tabicadas* by Rafael Guastavino Moreno (Garcìa-Gutiérrez 2000).

10. The amazing height of the Mole is grounded in reason of its tubular structure to double hull constituted from interlaced arches on a square plan, carried out without scaffoldings till the limit of their steadiness.
11. The development of the lantern of the dome in a shape of a pinnacle at many levels, like a pagoda, was conceived by Wren in the «Warrant Design» for the St.Paul's Cathedral in 1675, but with a carpentry in wood.
12. Those plans are kept in the Archivio Antonelli, Galleria Civica d'Arte Moderna, Turin. Caselli (1888) reports the site proposed by Antonelli for the Mausoleum: the Monte Mario in Rome (where today the Hilton hotel rises) or the Monte Cavi, site of the ancient temple of Jupiter, in the Colli Albani near Rome.
13. Conjecturally, the building seem high over 200 mt; nearly such to contain the Mole, and perhaps this one the Dome of San Gaudenzio . . .
14. This consideration limits every ideal reconstruction of the project to an approximate and not all defined hypothesis of the external shape, referred from typologic analogies.
15. Specifically, it is possible to apply to this building the considerations referred by Boullée with regard to the architectural type of the basilica, about how the greatness comes from the multiplicity and the combination of structures, from the diffusion of the light, from the variety of the perspective effects, rather than from their dimensions (Boullée [ms. ante 1799] 1967).

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The chapitel in the tower at the San Millan Monastery of Yuso in San Millan de la Cogolla (La Rioja)

Óscar Reinares Fernández

The study of the «chapitel» in the tower at the San Millán monastery of Yuso was undertaken following work carried out under the heading of *Estudios previos y redacción del proyecto de ejecución de refuerzo estructural y/o restauración de la iglesia de la Asunción de Nuestra Señora en el monasterio de San Millán de Yuso, en San Millán de la Cogolla. La Rioja* [1] which was awarded to us in an open competition in December 1998 by the Consejería de Educación Cultura, Juventud y Deportes del Gobierno de La Rioja.[2] San Millán's monastery of Yuso was declared a National Historical Monument in 1931 and a UNESCO World Heritage Site in 1997.

The site of the monastery is surrounded by a wall with an entrance to a large square which encloses the complex on the northern and western sides and another on the southern and eastern sides which includes the private orchard. The buildings radiate from the main cloister on the north side of which is the church, Figure 1. To the south is the complex of refectories and other monastic dependencies around the smaller cloister; to the east is the vestry (former chapter house). The library is on the first floor and to the west is the Hall of the Kings and the main staircase. A bay which is a westerly extension of the north side of the cloister includes the gatekeeper's lodge now converted into the Language Hall. Another in the same direction continuing on from the refectories includes the former abbot's chamber now a hotel.

The church, whose building work began in 1504 is of one nave in four parts and between the buttresses although slightly lower and intercommunicated through not very high round archways on tuscan pilasters are independent chapels, transept standing out both in plan and front elevation and a large presbytery finished rectangularly at the east end with slightly lower chapels on both sides. The supports for the nave are smooth cylindrical pillars on octagonal bases adjoining the previously mentioned buttresses supporting the transversal ribs and slightly pointed wall arches. The central nave and the transept is covered with rib vaults with curved liernes and side chapels with cul-de-four on pendentives towards the closing walls. In the presbytery there is an elliptical dome supported by pendentives too. At the foot of the church is the high choir resting on rib vaults with curved liernes in the nave and aisles and with a forged parapet on a segmental arch with relief statues on its front (Moya, inedited, Arrúe 2001, 2–12).

The present tower is situated to the east of the presbytery occupying the central part of the east end in the centre of the church back wall. In the lower part it has a special chapel called «the chapel of the relics» which connects the presbytery with the adjoining chapel of Montserrat and the old vestry giving it an important liturgical and devotional function which today has unfortunately been lost. The decision to build the tower in such a singular place was taken in 1619 after many failed building attempts including the collapse of the original north aisle in 1595 and the partial collapse of the east end in 1597. The tower building work was begun in 1629, when Friar Benito

Figure 1
San Millán de Yuso church. North façade from the access road to Suso monastery. (Photo: Óscar Reinares. October 2002)

Gonzalez was abbot and the work was carried out by the master builders Francisco del Pontón, Pedro de la Cuesta, Pedro Aguilera y Juan de Solano Palacios (Arrúe 2001, 36).

The tower in its front elevation is in three main sections, Figure 2. The tower is a 9.30 m sided square based prism with a height of 25.86 m from its base on the eastern side, finishing in an entablature from which two pyramid shaped pinnacles rise at each angle. Above the prism is another 3.47 m eight sided one, with a height of 9.98 m which serves as home for the bells with slightly rounded vanes and tuscan pilasters at the edges. Both sections are built of regular stone masonry on the outside and inside corners and dubbing out rubble on the surfaces between, solving the change from a square to an octagonal shape using brick squinches. Access to the bells is by a wooden ladder called «de Talavera» which rises beside the interior wall from the fourth floor of the tower.

Although at first the idea was to build the tower of quarried stone so as to be safer and less costly [3], finally it was decided to build a wooden chapitel which constitutes the upper section of the tower. The master craftsmen in charge of the building work were Pedro de Basave y Diego de Lizárraga, under the abbots Friar Benito Vicuña and Friar Benito de Salazar (Arrúe 2001, 40).

The crowning finish of the tower with the chapitel follows the idea developed in the Low Countries during the times of Phillip II (Nuere 2000. 172–177). The one in Yuso, Figure 3, has four sections and is crowned by a ball (B), weather vane (V) and the upper cross (C), with a total height from the bottom to

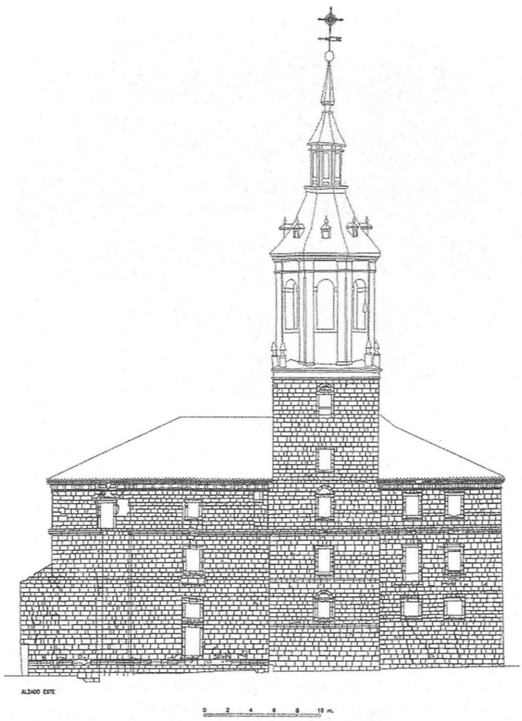

Figure 2
San Millán de Yuso church. East façade

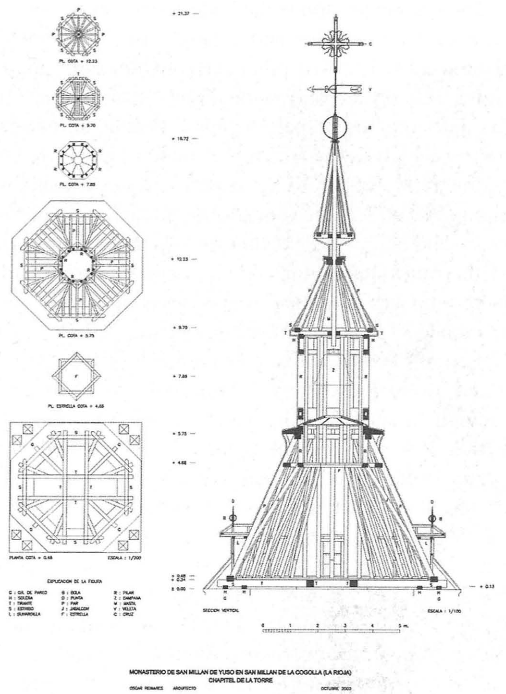

Figure 3
Chapitel. Plans and vertical section showing the various elements: wall thickness (G), wall plate (H), tie beam (T), tie bar (S), garret (L), ball (B), spike (D), rafter (P), brace (J), star shaped ring (F), pillar (R), bell (Z), mast (M), weather vane (V) and cross (C)

the top of the cross of 21.37m. It was built from a really elegant piece of pine and covered with lead sheets attached with iron hooks with great use of timber work, following indications of Friar Lorenzo de San Nicolás in his essay on Art and use of Architecture in which he warns of the danger to the chapitel caused by strong winds: «el peligro del chapitel causan los ayres violentos, pues ha sucedido arrancarle entero, y yo sé adonde sucedió: mas remediase este peligro con abundancia de madera» [4] (San Nicolás, C.XLIV,114).

The lower section of the chapitel is an eight sided truncated pyramid 5.75 m high following Friar Lorenzo's own ideas too,with eight garrets (L), one on each side, ending in ball (B) and spike (D). This pyramid rests on the top building work of the second section of the tower in two parallel 18x13 cm wall plates (H) which in turn rest on two pairs of right angled 25 × 25 cm tie beams (T) which resist traction forces at the base of the chapitel. Over the tie beams and the rest of the wooden planks which make up the base there is a ring of tie bars (S) made up of eight 25 × 20 cm beams with quarter sawing joinery which work as supports for the forty-eight 20 × 15 cm of variable length rafters (P) which make up the whole lower part. 15 × 15 cm braces (J) come out of the central pair each side and the eight angle ones which help support a star shaped ring (F) which stabilizes the whole. This latter piece is put at a height of 4.53 m above the chapitel base and is built of halve wood joint with a 45° turn in two square frame of four 19 × 15 cm beams joined in a mitre square which is the prime piece of the roof framing allowing completion of the complex transition from the first to the second section.

The second section is the lantern with an octagonal base of 1.15 m sides and a height of 4.75 m with sixteen 19 × 13.5 cm pillars (R), two at each angle, which rest on the above mentioned star. Actually it fits into the lower part using a simple perimetral impost which easily solves the union of the different geometrical shapes. The lantern as such contains eight 0.40 × 2.20 m vanes, one on each side of the prism and below these eight eyes which help to get rid of the rainwater, Figure 4. The upper section of the lantern houses the roman shaped great bell *La Bomba* (Z) made of bronze measuring outside 120 cm high, 101 cm inside and with a base diameter of 140 cm and about 1,600 Kgs heavy,[5] supposedly recast from a previous medieval one dated 1269. According to Father Peña the weight is slightly less, 1,300 Kgs (Peña 1994, 221). The bell has latin inscriptions in two bands which run around its perimeter in the upper and lower outer parts. They are 35 mm capital letters framed by two groups of three filets giving a total band height of 80 mm. Father Peña duly transcribed them as follows (Peña 1994, 221): «Ave Maria gratia plena Dominus tecum. Sancte Aemiliane ora pro nobis. Aemilianus me fecit» for the lower one and «Ecce + Domini nostri Jesu Christi: fugite partes adversae: vicit leo de tribu Juda» for the upper one. We have done brass rubbings of the lower one which says «AVE + MARIA + GRATIA + PLENA + DOMINUS + TECUM + SANCTE + AEMILIANE + ORA + PRO + NOBIS + AEMILIANUS + ME + FECIT +», Figure 5. The bell is also decorated with two big crosses one to the North and the other to the South between the bands and under the former appears the date 1269, Figure 6, which could refer to the date of the original medieval bell. What is clear above all is that the chapitel's layout was predesigned to house this bell in its lantern which happened between 1661 and 1665 under the abbotship of Friar Benito de Salazar. This detail apparently proved, conflicts with the account book payment details documenting the forging of the bell in 1677,[6] twelve years after the completion of the building of the tower.

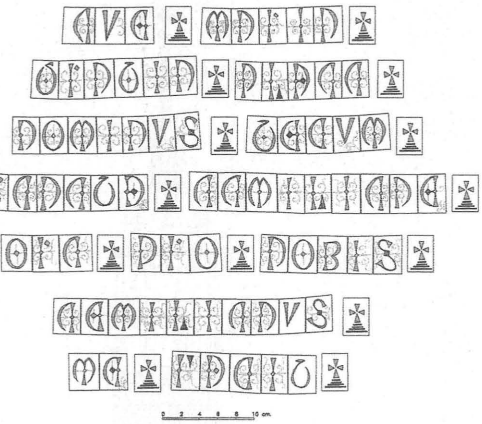

Figure 5
Latin inscription in *La Bomba* bell lower section

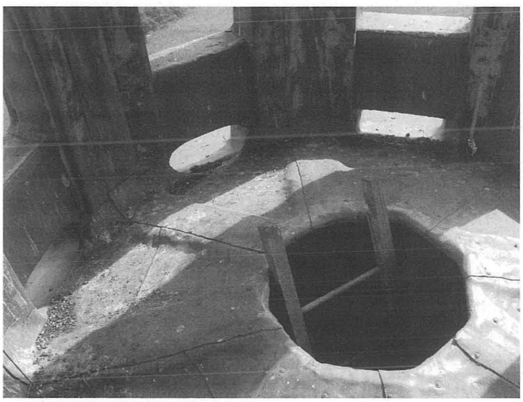

Figure 4
Chapitel lantern. View of the vanes, point of entry and eyes which help to get rid of the rainwater. (Photo: Óscar Reinares. October 2002)

Above the second section of the chapitel the lantern is covered by another pyramid slightly truncated of an octagonal base with height of 2.80 m. The way it was built is similar to that of the first section but in a lesser scale i.e. with sixteen 13 × 9 cm rafters (P) making the shape of the ceiling supported by a 19 × 16 cm tie bar ring (S) with quarter sawing joinery resting on two pairs of 90° angled 15 × 15 cm tie beams. In this case of the third section the tie beams also support the mast (M) from which the bell hangs and on which the framework of the chapitel's spire rest, Figure 7, exactly following Friar Lorenzo de San Nicolás again: «En chapiteles se asentarán los tirantes cruzados, (. . .), repartidos de suerte, que en medio hagan una caxa cuadrada, donde se fixa el árbol en que se hace fuerte el chapitel»[7] (San Nicolás, C. XLIV, 112).

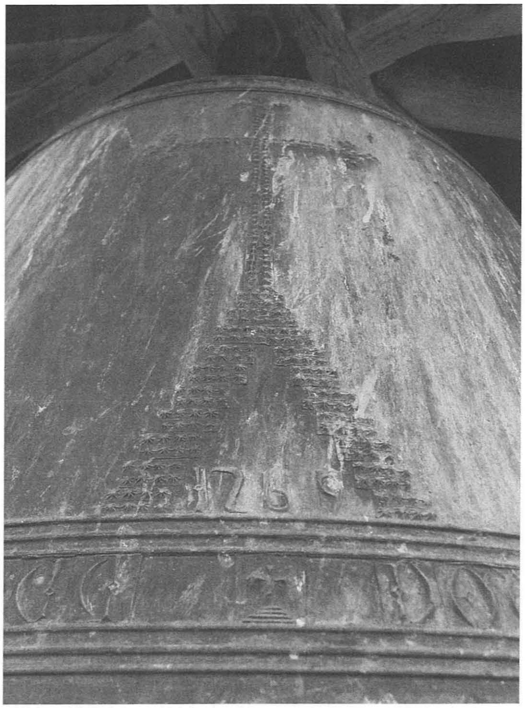

Figure 6
La Bomba bell. View from the north side showing the great cross and the date 1269. (Photo: Óscar Reinares. October 2002)

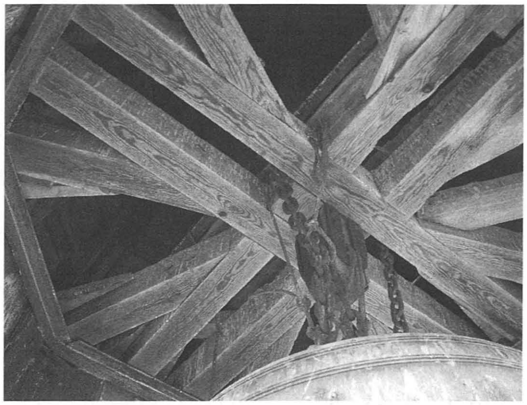

Figure 7
Chapitel lantern. View towards the lantern ceiling in which the lower part of the mast and the bell's hanging system can be seen. (Photo: Óscar Reinares. October 2002)

As has already been mentioned the fourth section of the chapitel is the spire for which supposed plans are included as still it has been impossible to know its original form. It seems logical that the mast of 15x15 cm would run throughout its length as a support for the ball (B), weather vane (V) and cross (C). The spire's height is 4.49 m and the top of the cross reaching 57.21 m which of course is the total height of the tower.

Since the completion of the tower in 1665, few documents refer to the chapitel. We know that in the nineteenth century, the monastery was abandoned for nearly fifty years although the church was still use by the parish and it has to be supposed that the chapitel was maintained properly. In 1887 the Provincial Monuments Commission carrying out a ministerial decree reported the non-existence of a lightning rod in the monastery which was duly installed later (now

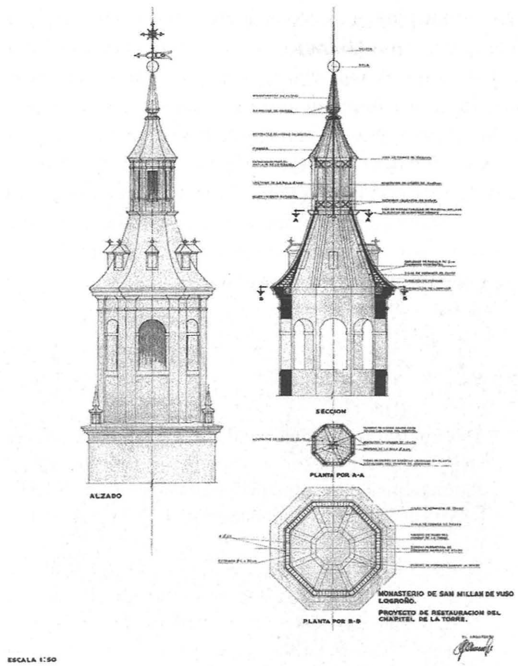

Figure 8
Drawing made by Fernando Chueca Goitia with the proposal he made for the chapitel's restoration which were never carried out

missing) on the east side of the chapitel at the height of the spire. In 1979 the architect Fernando Chueca Goitia instructed by the Ministry of Culture drew up a project for restoring the chapitel. Shocked by the terrible state it was in, he mentioned in the project's report: «El chapitel se encuentra en gravísimo estado, y su armadura de madera puede originar en cualquier momento una catástrofe. Hay que tener en cuenta el lugar donde está colocado el Monasterio de Yuso, en las estribaciones de la Sierra de la Demanda, un lugar frío y azotado por los vientos en los largos meses de invierno. En alguna de estas ventiscas, el chapitel podría venirse abajo y producir un verdadero desastre en el edificio, sin contar, caso que sería más lamentable todavía, con la posibilidad de que se produjeran desgracias o pérdidas de vidas humanas. Es por lo tanto muy urgente la restauración de este chapitel» [8] (Chueca 1979, 3). In the project the conservation of the wooden structure was deemed impossible so a new structure of reinforced concrete and steel was proposed following the original exterior shape. Fortunately during the restoration work (1980) this initial plan was reconsidered and finally only a fine steel strengthening was introduced carefully added to the wood which in this way alleviated the structural problems mentioned in the original report.

More than twenty years after the restoration and in spite of the fact that the chapitel keeps its original features, its condition cannot be considered good and a new restoration is needed to guarantee the complete conservation of this magnificent example of seventeenth timber roof structure.

Notes

1. The English translation would be: Preliminary studies and written project for structural reinforcement and/or restoration of the church of La Asunción de Nuestra Señora at San Millán's monastery of Yuso, San Millán de la Cogolla, La Rioja.
2. In the preparation of this work a wide technical and scientific team specialised in the restoration of historical monuments has taken part: historians, architects, archaeologists, chemists, geologists, civil and industrial engineers, technical architects and engineers, technical drawers and other technical staff. Special mention for their personal contribution in the study of the chapitel to Óscar Reinares Fernández (architect and project director), Begoña Arrúe Ugarte (Dr. in Art History), María Jesús Martínez Ocio (BA in Art History), Angel Atauri Furundarena (technical drawer), Pedro Benedicto Mena Miguel (technical drawer), Laura Iñiguez Lambriave (technical drawer) and Jaime de la Iglesia Chamarro (architect) and special thanks to the Agustinos Recoletos monastery congregation for all their kind help during the investigation.
3. «Y propuso su Paternidad que ya sabían auia vn maestro de yelssería, llamado Juan de Urriola, hombre muy diestro en su arte y hazendado como ya todos conocen, y que hará con mucha comodidad la obra porque es muy conuenible y deseoso de aprouechar esta dicha obra si le parezía que a este maestro se le diesse la dicha obra; todos dixeron que supuesto que conozen a este dicho maestro y están satisfechos que será bien se le de la obra; assí sea y se le de antes que a otro alguno y que en otro consejo se tratará de precio».
   «Yten se determinó por todos vnánimes y conformes que el chapitel de la torre nueba sea de cantería sillería y no de otra materia por ser más segura y menos costosa».
   (AHN, Sección Clero, Libro 6086 de actas del Consejo 1626–1640, fols. 120r. in Arrúe Ugarte, Begoña, Mª Jesús Martínez Ocio y Mª Cruz Navarro Bretón, *Fuentes documentales para el estudio del patrimonio histórico del monasterio benedictino de San Millán de la Cogolla (La Rioja). Siglos X-XIX*, Consejería de Educación, Cultura, Juventud y Deportes del Gobierno de La Rioja, inedited).
4. The English translation would be: the danger to the chapitel caused by strong winds which have even blown off completely, and I know where such has happened, so to remedy this danger use plenty of wood.
5. Taking as a reference the details offered by Professor Ernst Neufert in his famous treaty *Arte de Proyectar en Arquitectura* (Neufert 1964, 411), if *La Bomba* is considered to be a 138 cm diameter bell, its weight will be 1560 Kgs and its note do#^{4}.
6. «Yten pague a dos campaneros montañeses que fundieron tres campanas, la bonba, vn esquilón y la campana que se toca a comer, mil rreales de la fundición de estas tres campanas. Yten pague a los mismos ochocientos rreales por hazer dos campanas nuebas, vna grande y vn esquilón mediano.»
   (AHN, Sección Clero, Secular-Regular, Libro 6035 del gasto que se hace en las obras del Real Monasterio de San Millán de la Cogolla, fol. 26 r. in Arrúe Ugarte, Begoña, Mª Jesús Martínez Ocio y Mª Cruz Navarro Bretón, *Fuentes documentales para el estudio del patrimonio histórico del monasterio benedictino de San Millán de la Cogolla (La Rioja). Siglos X-XIX*, Consejería de Educación, Cultura, Juventud y Deportes del Gobierno de La Rioja, inedited).
7. The English translation would be: The chapitels will

rest on crossed tie beams (. . .) distributed so that in the middle there is a square gap where the tree which makes the chapitel strong will be fixed.

8. The English translation would be: The chapitel is in a terrible condition and its wooden structure could produce a catastrophe at any moment. You have to bear in mind where the monastery is situated, in the valley of the Demanda Mountain range, a cold windy place throughout the winter months. One of these windy days the chapitel could come falling down and so cause terrible damage to the building as well as the possibility of loss of life. Its restoration is of utmost importance.

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Loading tests involving historic structures, opportunity or risk?

Elke Reuschel
Johannes Vielhaber

Special features of buildings as historic testimonies

Buildings are built for a special purpose. The designated use dominates the structure and its design. Not many master builders lay claim to eternity. An awareness of transience of the material and changes in the requirements is omnipresent. Nevertheless, the value of a building for people far exceeds the actual intended use. After all, it is an objective part of the environment they experience and reflects everyday life, production and culture of the time of its construction more clearly than written or visual sources. Therefore, buildings are an important part of our cultural heritage.

Unlike musical and literary works of art, buildings are subject to destructive influences from wind and weather, damaging substances and organisms and intense utilisation. However, the, most significant damaging factor is a different one, as already observed by Dehio in a presentation he gave in 1905 in Strasbourg, which set a trend for the preservation of historic monuments in Germany: «And the people themselves contribute more to their destruction than the forces of nature. Architecture destroys architecture. This is how it has always been, and people just accepted it like an objective necessity». (Dehio 1905). Therefore, the superficial interest in a building is not based on a beautiful façade, an historic event or a new technology, but in its utilisation. If it is no longer relevant, people decide on its future destiny: demolition or preservation and conversion. In the most favourable case, an old building can become a mirror image of changing ideas about life, production and culture over a prolonged period. For this to happen, new uses keep having to be found for the structure that make it worth preserving for clients and preservers of historic monuments. Only then is the building prepared for the new utilisation requirements through the work of architects and engineers.

Due to the rapid development of structural engineering and the predominant orientation of training towards innovations, less and less practical experience and know-how about the management of historic structures and materials are available. How often do planners use forceful allegations that the old structure is no longer viable and therefore has to be replaced to disguise their uncertainty, lack of knowledge and ability to empathise with? An eloquent example is common practice of replacing of old timber joist floors with new reinforced concrete slabs. A different route has been used for more than 40 years in former Czechoslovakia, where the load carrying capacity of such ceilings is increased by a factor of 4 or 5 through the creation of a composite effect with concrete (Postulka 1997). This is the result of an examination of the old design, and the detection and compensation of weak points. Even from an economic point of view, this solution is very advantageous. Significant parts of the historic design are thus preserved for future generations, and any reinforcement is clearly attributable.

There can be no doubt that historic designs and structures do not meet all of today's binding standards, which have emerged from the know-how of generations. But does this mean that they should a priori be classified as unsuitable for the new utilisation requirements? Using calculations alone, it is often not possible to achieve compliance, notwithstanding the use of state of the art calculation techniques, because the calculations cannot be better than the model assumptions we make for old structures. Far more promising are experimental methods for determining the condition of the structure that are not based on models, but on reality. Loading tests can therefore help to explain the structural behaviour of old structures and utilise it for the new requirements.

EXTRA —A TECHNIQUE FOR EXPERIMENTAL STRUCTURAL SAFETY ANALYSIS

Development of the technique and state of standardisation

Loading tests are as old as construction history. The development has always been based on trying out and observing. The loading tests for new bridges that decided the fate of the master builders are almost proverbial. As early as 1925, normative regulations for loading tests existed as part of DIN 1045 for reinforced concrete buildings.

In the early 70s, the passages about loading tests were removed from the German standard. Calculation was therefore the only method available for the verification of adequate load carrying capacity. Only railway bridges continued to be subjected to a loading test using heavy load vehicles prior to commissioning. A different development occurred in the GDR, where experimental testing of buildings and components had the same normative status as calculations (1986: TGL 33407/04).

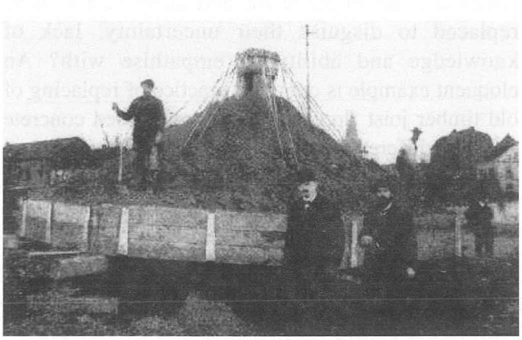

Figure 1
Loading test of the newly developed Möller girder; the inventor can be seen in the foreground (source: Quade, Reuschel 1994)

However, modern methods go far beyond the approaches mentioned. Experimental structural safety analysis is a very young branch of science that only emerged since the mid 80s. The German research project «EXTRA —in situ experimental structural safety assessment of buildings for the purpose of preserving the substance or alternative utilisation» carried out at the universities of Bremen, Dresden, Leipzig and Weimar plays a significant role. As part of the project, the methodical, scientific and technical preconditions for experimental structural safety verification for ductile building construction components were created and tested in many pilot objects. In subsequent years, this method was successfully used for a variety of structural designs and for bridge structures.

The «Guidelines for loading tests for concrete structures» of the German reinforced concrete committee have been in force since 2000. They specify the steps required for preparing and carrying out loading tests (assessment of the structural condition, test programme, implementation including maximum load criteria, evaluation taking account of the safety concept and test report), as well as the requirements for the test centre carrying out the tests. Internationally, there is also increasing interest in experimental structural safety assessments. Lewicki and Opitz provide a good overview.

Short description of the experimental structural safety analysis approach

Experimenting means influencing a test object in a controlled way and observing the response. Loading equipment is used for subjecting the structures to controlled influences. Metrology deals with the observation of the response of the structure. Figure 2 shows a diagram of the computer-aided procedure. What is new?

The loading equipment makes the effect of the load

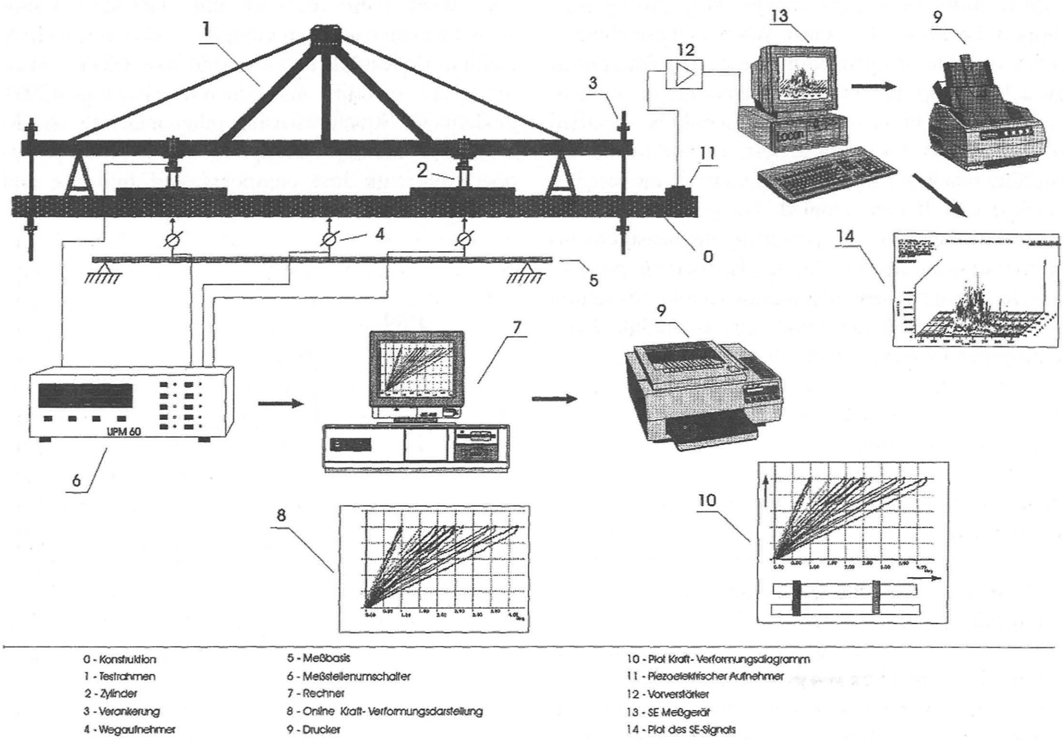

Figure 2
Overview of experimental load carrying capacity tests (source: Reuschel, Fiedler 2000)

reproducible in terms of magnitude, direction and change over time. It consists of force generation, force measurement and force transmission into the test object. For experiments with floors, the active load is generated via mobile hydraulic cylinders through oil pumps according to Figure 2, measured via load cells and distributed across the required load model via a load device. The reaction forces of the cylinders are absorbed by a steel load transmission structure (lattice frame, girder) and transferred into the existing structure. In this way, a closed force loop is created that can be adjusted according to the test requirements. This is done, for example, through anchoring of console profiles in the load-bearing masonry walls or via tie rods and cross bars below cross beams.

Of even greater significance is the question of load protection during experimental structural safety analyses, i.e. rapid relief in case of critical shape change conditions must be possible. So-called self-securing loading systems have to be provided. For bridges, a newly developed load vehicle has been available since 2001, which meets all requirements for a self-securing loading device.

The structural responses generated depending on the load are measured using suitable sensors, and stored and displayed on a monitor using a computer-aided measuring system. All measuring points are monitored simultaneously and in real-time. Load/distortion diagrams are generated that are similar to those of a stress/strain line of the relevant building materials. The formation of the load/distortion diagrams must be monitored thoroughly. Deviations from a straight line, i.e. changes in slope, indicate structural changes (e.g. crack formation, crack enlargement, local

plastification) or system changes (e.g. lifting of a support, breaking of a bond). Whether these changes are of a stable or unstable nature can be determined by a load stop and brief load holding. In order to avoid damage, deformation limits should be specified for the fitness for purpose test, depending on the building material used. Misjudgement of the monitor displays can thus be avoided. The procedure can be made more sensitive by accompanying measurements of the sound emission during the loading process, which can provide information about structural changes. To this end, sound sensors are placed in appropriate locations on the floors.

Safety considerations

A significant difference between experimental structural safety analysis and traditional loading tests lies is in the magnitude of the test load. Späthe provides the following concise description: «From a safety theory point of view, a loading test can be useful, pointless or even harmful. It is useful, if the information gained means that the safety index after a successful test is noticeably higher than before. The effort is pointless, if there is no noticeable increase in safety, because the chosen load level was too small or the load arrangement was inappropriate. And a lot of damage can obviously be done if the load level for a loading test is excessive». (Späthe 1994)

Conventional loading tests use the dead load of concrete slabs or steel plates, sand bags, heavy vehicles or similar, which are usually only part of the live load to be applied for the object being examined (see also Figure 1). They are suitable for checking mathematical models or for system identification, but they do not enable statements to be made about the safety of the structure and undoubtedly bear a higher risk in the event of concealed damage. The test load for experimental structural safety assessments should therefore be as high as possible, so that, in the event of a positive test result, the safety margin gained for increased load can be used for example, for changes in the floor structure or for higher live loads (Figure 3). On the other hand, it should not be too high, because the loading tests should not cause any damage that would reduce the load carrying capacity and fitness for purpose. Experiments therefore approach limits without precise prior knowledge about where these limits are. Important limit criteria are deformations such as elongation, changes in crack width or deflections that must not be exceeded. Such limits are specified for concrete structures (2001 guidelines). Structures using other materials should be treated correspondingly. In this case, close co-operation with test engineers and building and construction authorities is required.

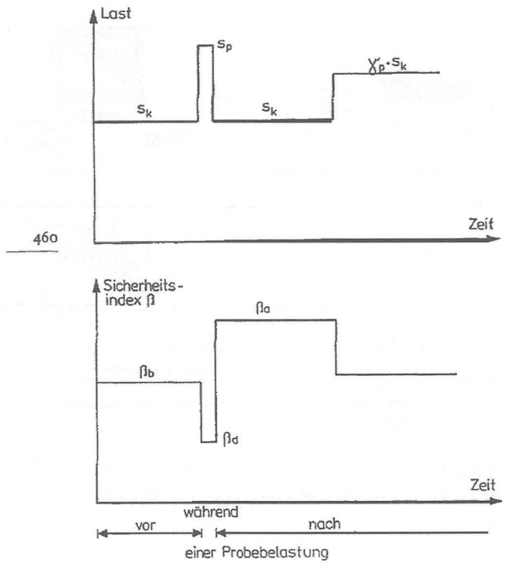

Figure 3
Basic curve for load S and safety index β during a loading test (source: Späthe 1994)

In order for experiments to become an opportunity for historic structures, rather than a risk, in addition to the measuring and loading equipment, detailed preliminary examination of the weak points of the construction, advance calculation of the expected measurement readings, and of course experienced and responsible test personnel is required, because the decision about a further load increase or the abortion of a test can never be made by following a certain recipe. The target load for the trial is specified based on the boundary state technique, using the same partial safety factors and combination coefficients as for mathematical verification.

Potential applications

Due to the specifications in the relevant standards, in Germany experimental structural safety analysis are only carried out in cases where mathematical techniques reach their limits. For example, meaningful and reliable structural documents are often not available for old buildings. As a result, a sophisticated building survey is required that covers not only the geometry of the structure, but also the technical details such as type and condition of the reinforcement, the building materials used etc. Particularly for the critical points of a building, this information is often difficult to obtain in a non-destructive or low-damage way, e.g. only in a very cost-intense way via radiographic examination, or not at all.

Properties of building materials can be determined, for example, via drill cores. However, if the results are scattered, the load-carrying capacity determined via calculation can easily be corrupted, because drill cores with high strength may be located at points with higher load and drill cores with lower strength at points with lower load —or vice versa. Furthermore, the direction of the core does often not correspond to the load in the building. Uncertainties in the assumptions for the material properties can also result from fire, corrosion or overload etc.

Loading tests are highly recommended, if there is uncertainty about the modelling of the structural behaviour of a structure, e.g. due to the contribution of components that are not part of the load-bearing section. Often, the modelling of damaged structures or components is also difficult. Experimental verification is also appropriate in cases where historic structures do not meet modern standards for the constructive design of the components.

All these preconditions often apply to protected objects. Some application examples were described in (Quade, Reuschel 1994; Steffens, Wolters 1997; Steffens 2001). Studies carried out on historic ribbed floors are presented below.

EXAMPLES FOR EXPERIMENTAL STRUCTURAL SAFETY ASSESSMENTS

The problem of historic ribbed floors in Germany

After the take-over of the property of the East German «National People's Army» by the Federal Armed Forces and the withdrawal of the Red Army troops based in (East) Germany, the desperate need for refurbishment of most of the barracks, some of which had been built before World War 1, became apparent. Both the continued utilisation for military purposes and the search for new civilian utilisation options required statements about the existing load carrying capacity of the floor structures to be made.

In addition to the frequently poor structural state of preservation, missing or incomplete building documents hindered structural recalculations, so that initially comprehensive diagnostic structural studies for determining the floor constructions, the materials used, the placement of reinforcements and the damage characteristics had to be carried out. In order to keep the diagnostic effort within reasonable limits, usually —conservative— structural assumptions based on the knowledge level at the time when the buildings constructed had to be made. The permissible floor loads calculated on this basis did often not match the designed utilisation requirements or contained large uncertainties, so that the refurbishment concepts provided for cost-intensive reinforcement or replacement measures for ceilings and beams. The only alternative to this approach was experimental structural safety assessment of these components.

Construction, calculation and load carrying capacity of reinforced concrete ribbed floors

Reinforced concrete ribbed floors are slab-and-beam floors with a maximum clear distance of 70 cm between the ribs. The thickness of the pressure plate should be 1/10 of the rib distance, but no less than 5 cm. The minimum width of the ribs should also be 5 cm. The ribs may be visible, although for achieving a level ceiling, the voids between the ribs may be filled with light-weight, non-load-bearing hollow blocks made of gypsum, breeze concrete, brick or similar. The only load-bearing components are the concrete pressure plate, the narrow concrete ribs and the flexural tensile reinforcement within the ribs.

This active static principle is the main difference to reinforced block floors, whose load-bearing effect is a result of the synergy of brick, steel and cement mortar, i.e. the stones are used for absorbing the compressive stresses. Standardisation efforts for level ceilings with

brick and iron reinforcements go back to the year 1905. In 1913, a distinction was made for the first time between rib and block slabs and reinforced block floors (Berlin police headquarters, 1913), but the final definition in the above sense did not appear until 1925 (German reinforced concrete committee, 1925).

During the first few decades of the 20th century, a large number of, sometimes very different, floor types were developed, based the on the ribbed floor principle. More frequently used floor types were, for example, the Koenen slab (Figure 4a), the Rella slab with rib distances of 50 cm and infill blocks made of gypsum, slag or cement concrete (Figure 4b) and the Ackermann slab with hollow blocks of 30 cm width (Figure 4c). After World War 2, DIN F slabs with prefabricated beams and infill blocks that played a role in the compression zone became very significant. Structural requirements in terms of transverse reinforcement, the shear reinforcement and the arrangement of transverse ribs were developed during this time for ribbed floors.

Due to

- — the assumptions that had to be made about the material strengths for the reinforcement steels used at the time and for the concrete,

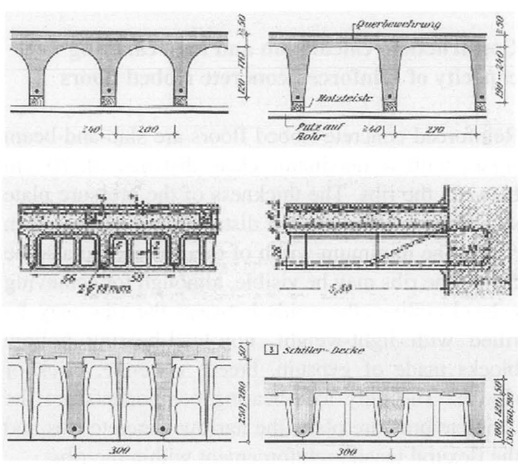

Figure 4
Examples for ribbed floors constructed before World War 2
a) Koenen slab, (source: Ahnert, Krause 1991)
b) Rella slab, (source: Bargmann 1993)
c) Ackermann slab, (source: Ahnert, Krause 1991)

- — the predominantly longitudinal load transfer due to the small amount of transverse reinforcement and the arrangement of transverse ribs, and
- — partly inadequate shear reinforcement

even the recalculation of the floor constructions with the aid of techniques commonly used today only provided little options for mathematical verification of increased live loads due to new requirements and/or increased dead weight of the ceilings through modified floor construction (protection from structure-borne sound, thermal insulation and fire protection).

Studies in former barracks in Saxony

In a barracks complex in Saxony, a building constructed before or during World War 1 was to be used as an accommodation block. However, no structural documents were available that would allow conclusions about the load carrying capacity of the existing ceilings to be drawn. The organisation managing the project had already commissioned an expert report based on a diagnosis of the building and static recalculation. However, even with a reduction of the requirements based on P.3 of the «civilian» DIN 1055, this did not produce permissible live loads, so that complex and cost-intensive structural measures appeared unavoidable.

A large proportion of the total ceiling area of approximately 3,600 m^2 was diagnosed as a reinforced concrete ribbed floor construction with a rib distance of 50 cm (probably type Rella), the remainder was identified as massive reinforced concrete slabs (partly designed as continuous systems). The clear spans of the ribs had been adjusted to the spatial requirements, with a maximum of 4.6 m. Consequently, the cross section of the reinforcement inserted between the ribs also varied, between 2.36 and 3.92 cm^2. No transverse reinforcement was present, and there were clear cracks along the direction of the effective span. At all levels, the hollow blocks had a height of 17 cm, the thickness of the compression concrete fluctuated between 3 and 5.5 cm, the concrete strength determined from drill core tests was between B10 and B15 in different areas.

At the suggestion of the consultants, the client decided to have the actual load capacity of the ceilings determined via an experimental analysis of the load carrying capacity. The aim of the studies was

the verification of the maximum distributed loads the ceilings could accommodate, taking account of the required future live load level according to DIN 1055 (accommodation block), in order to have a certain amount of design flexibility. The tests were to be carried out for the existing state of construction of the ceilings, without causing damage that would impair the load carrying capacity and fitness for purpose during the intended period of future utilisation.

In the current building, five reinforced concrete ribbed floors, which had shown unfavourable diagnostic results in terms of reinforcement, span, compression concrete slab and damage, were specified for the loading tests. The loading equipment was installed on or below the ceilings to be tested, see Figures 5 and 6. The test loads were determined based on the safety concept of the relevant guideline (German reinforced concrete committee 2000), with factors added, for example, for the existing dead weight due to the diagnosed thickness variations of the floor layers, for the scatter in material properties, for variable loads and for the transfer of the test results to similar areas that had not been investigated. As a result, the live loads to be applied at this site were realised in the test with a global safety factor of $\gamma \geq 1.82$.

Due to the limited space available, the measuring instrument, the computer and the monitor as well as the hydraulic pump were installed in the corridor outside the spaces included in the examination. For recording the ceiling deflections, inductive displacement transducer were installed in a transverse and longitudinal grid on the underside of the ceilings examined.

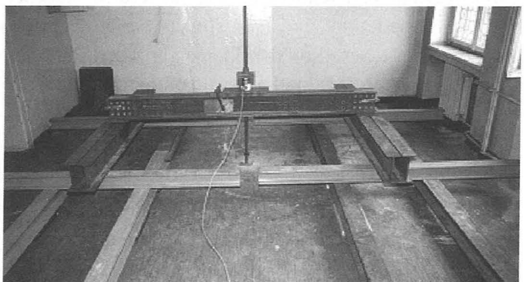

Figure 5
Load distribution on 16 individual load transfer areas of the reinforced concrete ribbed floor to be examined

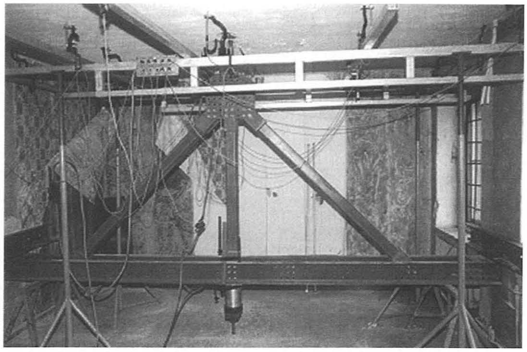

Figure 6
Transfer of the force generated by the hydraulic cylinder into the load-bearing walls with the aid of a steel frame construction; below the ceiling being examined, the measuring base with displacement transducers arranged in a grid can be seen

The loading test according to (German reinforced concrete committee 2000) was carried for each ceiling live load to be verified in a loading/unloading cycle, for which the behaviour of the structure was observed and analysed online. This also included a creep test for each target live load to verify reliable load transfer via the ceiling. Figure 7 shows examples of load/distortion diagrams for a ribbed floor subjected to a load increase test, Figure 8 shows a creep test.

As a result of the loading tests, a live load of 5.0 kN/m^2 could be recommended for the reinforced concrete ribbed floors of this barracks building. The deflections under this working load were less than 1/2600 of the span. Since the loading tests carried out at the reinforced concrete slabs were also successful, the building could be designated for the new utilisation without fundamental ceiling reinforcement measures, thus providing significant savings in building costs. The supporting structure as a testimony of a certain era-defining barracks architecture could thus be preserved.

Studies in a Spanish embassy building in Berlin

Following the decision of the German parliament to reinstate Berlin as the capital of Germany, numerous ministries, public authorities, embassies, associations

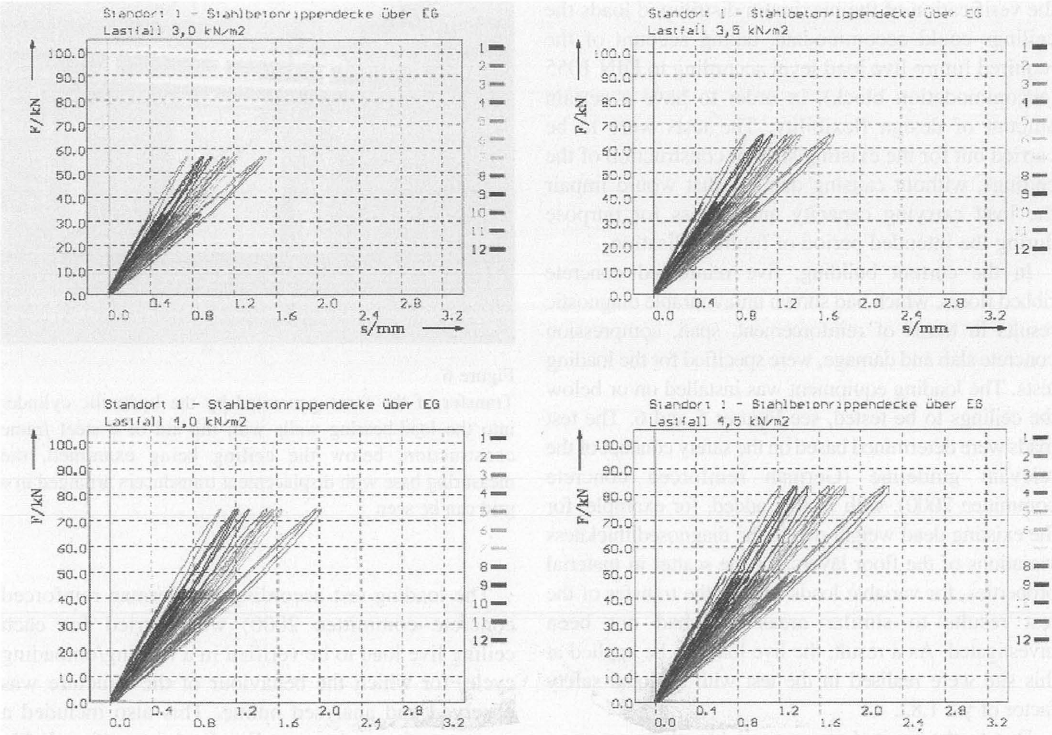

Figure 7
Load/distortion diagrams with several loading/unloading cycles for a reinforced concrete ribbed floor subjected to a load increase test for live loads of 3.0 / 3.5 / 4.0 and 4.5 kN/m²

etc. moved to Berlin. In many cases, existing buildings were repaired or modified and adapted to current requirements. In a number of cases, this also required experimental verification of their structural safety, which was usually carried out based on the guideline for loading tests (German reinforced concrete committee 2000).

As part of the refurbishment of an embassy building, reinforced concrete slabs made from semi-prefabricated components with in-situ concrete layer were installed. Inadequate support during the placing of the concrete led to significant deformations that were corrected after a few hours through intermediate supports. The hardening state of the ceiling was not checked at the time when the supports were installed, and it was feared that the ceiling may have been damaged due to the late installation of the intermediate supports, particularly in terms of the bond between prefabricated and in-situ concrete. At the request of the client, a test programme for the experimental verification of the structural stability was developed.

The test was based on the Spanish concrete standard EHE 2000, with the load specifications based on the Euro codes. In contrast to many other guidelines, this standard not only includes the option of experimental verification, but also detailed information about the experimental procedure and the criteria that have to be met. These include the following:

- Application of the maximum load in 4 stages
- Measurement of the distortion directly after reaching each load level and after 30 minutes
- Creep test after reaching the maximum load over 24 hours; Distortion measurement every 8 hours

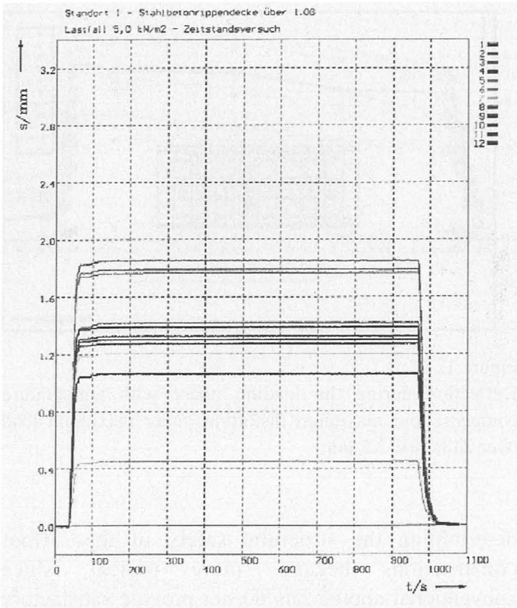

Figure 8
Creep test at 5.0 kN/m² for a reinforced concrete ribbed floor

— Unloading in four stages with a 15 minute dwell period at each stage
— Creep test without load over 24 hours; Distortion measurements every 8 hours

The limit criteria are:

— The test is considered to have been passed, if the maximum distortion is less than $L^2/(20000\ h)$.
— If this value is exceeded, the permanent deformation after removal of the load must not be greater than 25% of the maximum distortion.
— If this is not the case, the loading test should be repeated. The permanent maximum distortion must now be less than 20% of the maximum distortion under load.
— The formation of cracks that could affect the durability is not permissible.

Such specifications provide the engineer with a tool that defines at least the main data. They go far beyond the data commonly provided in most other European standards. Within RILEM working group TC 125, attempts to find a uniform regulation had been made in the past. This has not yet been possible, since the national boundary conditions are too varied. On the other hand it became clear that, even without such rules, «design by testing» is not an invention of recent years, but common practice for a limited number of testing institutes, who use the tool very responsibly.

In deviation from the original concept of using water as the load (this would have required the creation of a 95 cm high water basin; in the event of failure, more than 40 m³ of water would have poured across the building site; furthermore, due to the limited water supply, this would have required a very long test duration), four frames were constructed on site, which were back-anchored to the supports via tie rods. The load was generated via small hydraulic cylinders that created a load in the «fifth-points» via load distribution girders.

The distortions were measured in longitudinal and transverse direction in the centre of the span measuring approximately 4.50 × 9.00 m², also the support distortions, the temperature and the temperature-related distortion of the measuring frame below the ceiling. Figures 9 and 10 show the experimental set-up.

Figures 11 and 12 show the results of the distortion measurements. Figure 12 corresponds to Figure 11, but includes a temperature compensation of the deformations of the measuring frame.

In conclusion it can be noted that only one load cycle was required for verifying adequate structural safety and fitness for purpose and for stopping the endless discussion about potential damage and its significance. This would not have been possible without the willingness of the client and the engineers, both on the Spanish and on the German side.

Summary evaluation of the studies

Reinforced concrete ribbed floors developed during the first decades of the 20th century make up a large part of the building substance of that time. With the diverse demand for conversion of this building substance since the early 1990s —not least with regard to former barracks buildings— the problem of

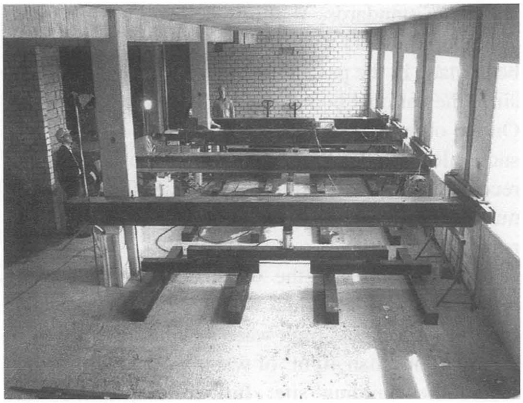

Figure 9
Experimental set-up with test frame and load distribution girders on the ceiling

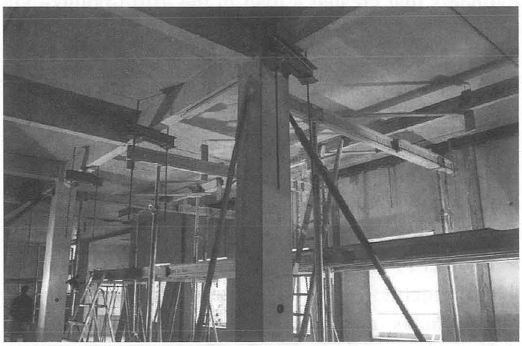

Figure 10
Experimental set-up and measuring frame below the ceiling

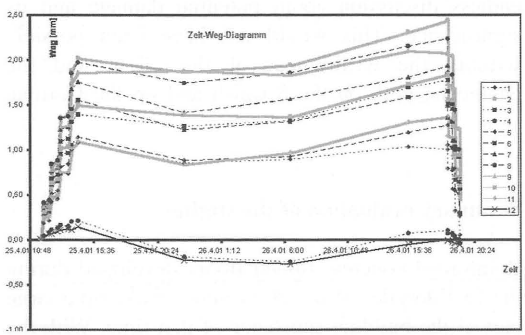

Figure 11
Deflection during the loading phase without temperature compensation

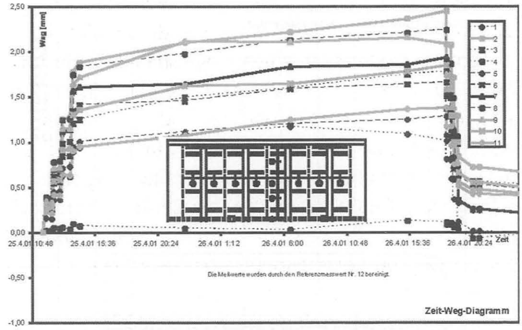

Figure 12
Deflection during the loading phase with temperature compensation; maximum distortion under maximum load over 24 hours: 2.5 mm

determining the structural safety of these floor constructions became more topical, since conventional approaches do not provide satisfactory answers. The load carrying capacity of ribbed floors established via experimental structural safety verification according to (German reinforced concrete committee 2000) could be used without a reduction in safety levels, not only for the example presented, but also for other cases. For theses floor types, working loads of up to 2.5 kN/m^2 higher than those identified by calculation were shown to be safe.

The reserves ascertainable in loading tests are based on the actual monitoring of the load-bearing effect including the support conditions, and on the existing material strengths. For the ribbed floors, in practice the first factor means: the end sections are often structurally obstructed or distorted, thereby enabling the utilisation of the vault effect of the compression concrete. On the other hand, the transverse distribution of the loads through the compression concrete layer, the contribution of the infill blocks in areas with good bond, the partly load-carrying floor layers etc. are taken into account.

These influences can also be demonstrated in experiments on other historic floor support structures such as reinforced block floors, timber joist floors or massive reinforced concrete slabs. In many cases, the magnitude of the ascertainable load reserves justifies the use of this undoubtedly costly verification procedure, if it enables expensive reinforcement, demolition and reconstruction work to be avoided and

if enables continued utilisation of the existing spaces. Based on the diverse experience in the application of experimental structural safety assessments for historic floor structures —both in protected and other buildings— the risk during the loading tests can be minimised through a thorough diagnosis of the structure, preliminary calculations and experienced testing staff. The chances of preservation of the historic structure, either in unchanged or only slightly modified form, are good. In each case, the recommended load capacity of the ceilings resulting from the structural safety assessment justified the experimental effort.

In the second example, the technique was used for a new design, whose structural behaviour had been assessed differently by different experts. Considerations comparable with those for the assessment of the structural safety of historic structures were able to provide valuable clues about the actual behaviour. Considerations and calculations based on theoretical considerations alone would have been fruitless.

Summary

Unlike testimonies of cultural history from the areas of music or literature, buildings are subjected to strictly objective utilisation and to harmful influences and permanent changes. Buildings are usually only designed for a limited service life and for a certain purpose. As a logical consequence, the replacement of buildings through new buildings is the rule. Only few buildings are preserved as testimonies of the history of technology due to their aesthetic and cultural significance and are treated as historic monuments. If such exemplary significance is not apparent, it is often merely the usability, closely related to structural stability, which decides the further destiny of a building.

The method of experimental structural safety assessment, methodologically and technologically developed at the end of the 1990s, can, in principle, be used both for protected buildings and for other historic structures. As a largely non-destructive loading test, it can make a significant contribution to the stability analysis of historic structures, if original computational or currently available techniques fail to provide satisfactory answers due to inappropriate or missing data or due to changes in utilisation requirements. Detailed analysis of the behaviour of a construction under controlled loads can provide valuable insight into the interaction of different structural elements, into any damage that may exist or into material ageing. This in turn can be used to minimise or avoid irrevocable interventions into the building substance. Preservationists and interested building owners therefore have the opportunity to critically question the argument of «lack of load-bearing capacity» often used by planners and to come up with new solutions. Significant cost and time savings are often an important side effect of an experimental structural safety assessment.

This paper uses selected examples of the application of loading investigations on historic structures to introduce and discuss preconditions, technology, methodology, safety and cost effectiveness of the technique.

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Quincha architecture: The development of an antiseismic structural system in seventeenth century Lima

Humberto Rodríguez Camilloni

The introduction of *quincha* construction in the City of Kings or Lima during the middle of the seventeenth century marked a decisive turning point in the devel- opment of Spanish colonial architecture along the Peruvian coast. Not only did this ingenious antiseismic structural system provide a definitive solution to the earthquake problem that had plagued several generations of builders since the founding of the viceregal capital by Francisco Pizarro in 1535, but it also permitted the creation of monumental and lofty interior spaces which paralleled and even rivaled European designs. Surprisingly, however, *quincha* construction has received only a general and inadequate treatment in the artistic literature of Spanish colonial architecture; its full impact still awaiting recognition in the history of construction. [1] In an effort to help fill this void, this paper investigates the earthquake-proof system of *quincha* and its formal implications, as a cornerstone in the history of South American colonial architecture.

In the viceroyalty of Peru, possibly no greater challenge confronted the colonial architects than that of designing buildings that could withstand the frequent earthquakes. Time and again European and viceregal architects had seen the failure of their efforts, including the anachronistic use of Gothic ribbed vaulting in the Cathedral of Lima following the earthquake of 1609 because it was believed it would provide a more resistant structural system. [2] Nevertheless, only with the construction of the church of San Francisco in 1657–74 (Fig. 1) was a more

Figure 1
Constantino de Vasconcelos and Manuel de Escobar: Lima, Church of San Francisco, west façade, 1657–74 (photo of 1973)

effective solution to the problem found through the use of the antiseismic system of construction known as *quincha* construction. Credit for this revolutionary innovation is given to its designer, the Portuguese architect Constantino de Vasconcelos (d. 1668), and his Peruvian assistant Manuel de Escobar (1639–1693), who supervised its construction until completion. [3] Vasconcelos' originality, however, consisted in adapting an ancient Pre-Columbian system of construction for the complex forms of different types of vaults that a large scale building required. The term *quincha* is in fact derived from the Quechua *kencha* and is synonymous of *bahareque*, typically used to identify the walls of primitive huts or of other simple constructions made of cane or bamboo and mud by the indigenous peoples of the continent (Fig. 2). [4] A good description of these structures is given by Bernabé Cobo in his *Historia del Nuevo Mundo* (1613–1653):

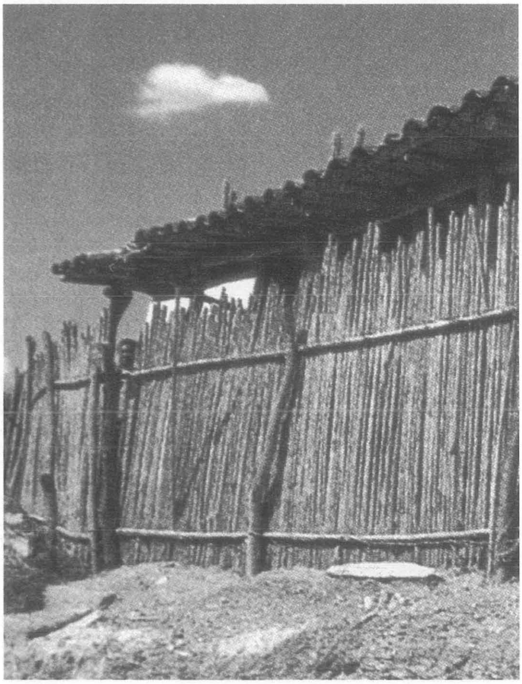


Figure 2
Primitive South America: Traditional hut showing *bahareque* or *quincha* wall construction (from Federico Vegas, *Venezuelan Vernacular*, 1985)

On the plains of the seacoast, there are two types of houses. Some are of *bahareque* and others are of earth and adobe. Those of *bahareque* have for walls and enclosures a very tight lattice woven likewattle. In making it they set certain thick canes or poles in the ground very close together, and at about two cubits from the ground, the run a reed in between in the way of a weft, leaving on each side half of the above-mentioned poles set in the ground, which cross over that lateral reed like interweaving; at a similar distance another lateral reed is placed, and in this way with three or four lateral reeds which are crisscrossed and interwoven between those poles that stand upright, they have completed a wall more or less two estados in height. We call this type of wall *bahareque,* taking the word from the Island of Hispaniola or Tierra Firme, while the natives of this kingdom use the term *quencha.* Some daub this *bahareque* or wattle with mud; others do not. The roof is constructed over this wattle, and since in this land it never rains, the roof requires no more workmanship than a covering of branches for protection from the sun; it was made with lateral poles and a matting of reeds on top. This is not a sloping roof; rather it is flat and level like a terrace. These houses of bahareque are in the form of a square, very humble, small, and low. This is the style of the majority of the houses of small towns and settlements of the Indian fishermen who live on the coast. [5]

The arid climate of the Peruvian coast noted by Cobo made *quincha* an economic, practical and durable system of construction, except during the rare episodes of «El Niño» phenomenon which brought torrential rains and major destruction to the settlements in the region. The primary materials for *quincha* construction are wood for the structural frame and cane or bamboo for the fill-in webs. The woods most commonly used in Lima were oak (*roble*) and cedar (*cedro*), strong woods resistant to insect infestation that had to be imported from Ecuador or Central America. There are also different types of bamboo (depending on the geographic location) exhibiting physical variations most noticeable in the thickness of the stems, and in the size and distributions of the nodes, internodes, and branches of the culms. For example, the *Bambusa arundinacea* is a thick-walled bamboo with inflated nodes and heavy, solitary, thorny lower branches (Fig. 3, A); the *Bambusa textilis* is a thin-walled bamboo with cylindrical internodes, non-inflated nodes flared at the sheath scar, and branch buds lacking at the lower nodes and tardily developed above (Fig. 3, D); whereas *Bambusa vulgaris* is a moderately thick-

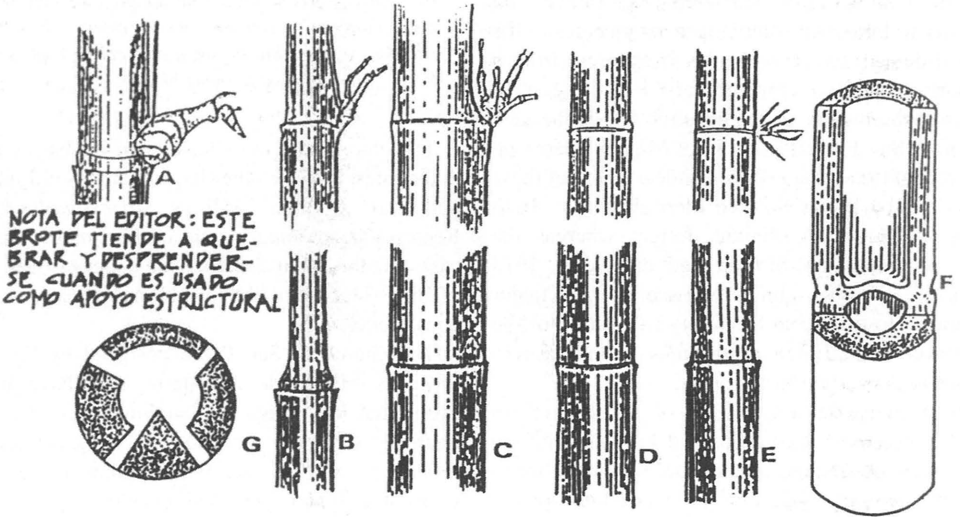


Figure 3
Examples of different bamboos with structural variations in the nodes, internodes and branches of the culms (after V. Hartkopf, *Técnicas de construcción autóctonas del Perú*)

walled bamboo, with inflated nodes, dormant branch buds below, and prominent branch complements above (Fig. 3, C). It should be noted that in all bamboos the diaphragm forms a transverse strengthening structure at each node. [6] By the time the Franciscan community commissioned Vasconcelos to design a new church to replace an earlier structure that had collapsed in 1656, his reputation as one of the leading architects of the viceroyalty had been well established. His impressive credentials as «nuevo Arquímedes en las Matemáticas, Platón en la Filosofía natural, y Diógenes Estoico en la vida de la naturaleza filosofal»—according to a contemporary source [7]—also included work as military engineer in the mercury mines of Huancavelica in 1643 and two years as a designer of fortifications in the port of Valdivia (Chile), for which he had earned the prestigious title of «cosmógrafo e ingeniero mayor». [8] The choice of Vasconcelos as the designer of the church of San Francisco was therefore understandable, but it is also clear that from the very beginning the *limeño* assistant Manuel de Escobar was given the full responsibility of the execution of the project. Thus, according to the notarial contract signed in Lima on June 14, 1659 by Escobar and don Juan Santoyo de Palma, «síndico de la fábrica de San Francisco», it is stipulated that Escobar would assume the obligation of directing and overseeing the construction of the church following the plan and design of Vasconcelos:

> Manuel de Escobar, como tal oficial de albañil, se obligó de trabajar y que trabajara en la obra de la dicha iglesia desde hoy dia de la fecha de esta escritura en adelante hasta que se acabe la dicha iglesia por precio de tres pesos de a ocho reales cada dia de trabajo, trabajando de manufactura personalmente y haciendo oficio de aparejador, maestrando toda la dicha obra siguiendo en todo la planta y disposición de don Constantino Basconselos [sic], sin salir de su orden en quanto a la disposición y fábrica de dicha iglesia, sin pedir más precio ni otro concierto en ningún tiempo mientras durare la dicha obra, hasta acabarse la dicha iglesia de todo punto ni poder salirse a otra obra dentro ni fuera de la dicha ciudad, sinó sólo a la de la dicha iglesia de Señor San Francisco. [9]

The details of this contract also help explain how it was possible for Escobar to carry on with the project alone after Vasconcelos' death in 1668, for by that

time he had acquired sufficient experience and authority to introduce some important changes to the original design. Evidence of this is apparent from a comparison of two contemporary engravings that appear in the history of the construction of the new church of San Francisco by Fray Miguel Suárez de Figueroa and Fray Juan de Benavides. [10] One of these engravings by Pedro Nolasco Mere datable c. 1673 shows Vasconcelos' original design; whereas the other, by Benavides himself and datable c. 1674 shows the church as built by Escobar with major alterations noticeable in the heavy rustication of the twin towers and different proportions of their bases in relation to the central frontispiece.

The design and construction of the Franciscan church presented Vasconcelos and Escobar with the most serious challenge of their professional careers and gave them the opportunity to study the problem of an effective antiseismic structural system anew. The challenge involved unusual complications since the new edifice had to incorporate substantial portions of the earlier structure, including the subterranean galleries that had served as catacombs since the sixteenth century and had weakened the brick foundations. The final solution arrived at by Vasconcelos and Escobar was, from any point of view, a strike of genius. It consisted in adapting *quincha* construction to the complex forms of the roofing structures, including the dome above the transept, the vaults, and also, as will be seen later in this study, the arcades of the second story of the main cloister. These monumental forms, consisting of plaster-coated webs of bundled and matted reeds on timber frames, were reinforced by strong cane bent to produce the desired curvilinear shapes (Fig. 5). Light, yet elastic enough to survive the severe earthquakes, *quincha* allowed for flexibility of formal and spatial design. At the same time, the stucco covering gave the visual impression of masonry construction, an effect greatly enhanced by rich geometric ornamentation in relief. Thanks to this innovation, the vast and luminous interior spaces of San Francisco were able to survive virtually intact for over three hundred years.

When viewed for the first time upon their completion, the *quincha* vaults of San Francisco (Fig. 6) were appropriately compared to the Galapagos tortoise shells and to the sails of a ship blowing in the wind by Suárez de Figueroa:

> [*son como*] *las conchas del Galápago* [*que*] *muestra*[*n*] *la parte convexa, y cóncava, no en esfera, sinó en arco triunfal, y las velas de un navío con próspero viento llenas,* [*las*] *representan muy bien.* [11]

This impression must have been in sharp contrast to the interior of the other large churches in Lima that had flat wooden ceilings (*artesonados*) with Renaissance or *mudéjar* decoration or, as was the case with the Jesuit church of the college of San Pablo of 1624–34, Gothic ribbed vaulting of heavy masonry construction.

The church of San Pablo designed by the Jesuit architect Martín de Aizpitarte may have in fact influenced the design of San Francisco, since both churches share the main features of a central nave flanked by single aisles with cupolas and a domed transept. But the plan by Vasconcelos (Fig. 4) is much more complex, for it is a *Caravaca* cross with a fully developed double transept in the eastern end and, in contrast to the uniform rhythmic articulation of the chapel-aisles of San Pablo, it has a triadic sequential organization of the side chapel bays and arches leading toward the main transept. Moreover, the nave of San Francisco is covered by a barrel vault supported on transverse arches and cut at each bay by lunette windows that accentuate a distinct airy feeling (Fig. 5). Here the interior wall measurements of the length of the nave (approximately 262. 48 ft.) and

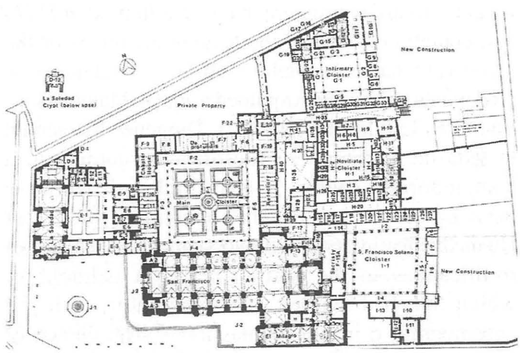


Figure 4
Lima: Church and Monastery of San Francisco, general ground floor plan in its present state (after H. Rodríguez-Camilloni and V. Pimentel Gurmendi, *Proyecto Integral para la Conservación-Restauración . . . del Convento e Iglesia de San Francisco de Lima*)

Figure 5
Lima: Church of San Francisco, interior view of dome and transept (photo before 1940 by L. A. Rozas)

Figure 7
Lima: Church of San Francisco, exterior view of roof damaged by the earthquake of October 17, 1966 (photo of 1967 by A. Guillén)

length of the main transept (approximately 131.24 ft.) yield the simple ratio 1: 2, which is consistently used also for the height of the arcades of the nave in relation to its total height and for the width of the arches in relation to their height. [12] Thus Vasconcelos succeeded in designing the interior spaces with the classical grandeur that best suited his aesthetic ideals, while making the building structurally sound so that it would withstand future earthquakes.

Old photographs of the roof of the church of San Francisco (Fig. 7) taken after the earthquake of 1966 permit an appreciation of how *quincha* construction was adapted to the vaulting system that were

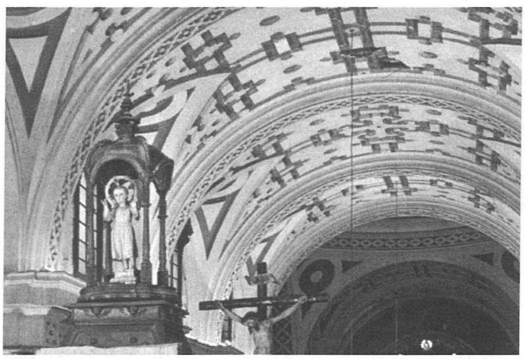


Figure 6
Lima: Church of San Francisco, interior view of nave vaults (photo of 1974 by T. Cusman)

required. The webs of cane fastened with leather straps to the wooden frames are visible, with exterior protection provided by thin flat tiles laid on a coat of mud (*torta de barro*). In the interior, the facing of a layer of white stucco consisting of geometric patterns of Renaissance and *mudéjar* origin is applied to the intrados of the vaults and supporting arches; and continued on the masonry piers and walls, achieving a total visual unity (Fig. 5). For the construction of the wooden frames, it is very likely that Vasconcelos would have relied on European models, such as those illustrated by Philibert De L'Orme in his *Le Premier Tome de l'Architecture* (Paris, 1567). Architectural treatises that were printed in Europe, particularly since the sixteenth century on- wards, were widely circulated in the Spanish American colonies thus providing an important didactic tool and source of inspiration for designs. As I have shown elsewhere,[13] De L'Orme may have also served as a source for some of the decorative patterns found in the interior and exterior of the church, i.e. for the heavy rustication that Escobar used in the towers. On the other hand, the structural design of the present cupolas of the twin towers which replaced their original third stories after the earthquake of 1746 (Fig. 1), appear to be derived from models in Fray Lorenzo de San Nicolás' *Arte y Uso de Arquitectura* (Madrid, 1633–64).[14] The dome of the church of San Francisco measuring approximately 36.9 ft. in diameter and rising to a height of 85 ft. up to the apex

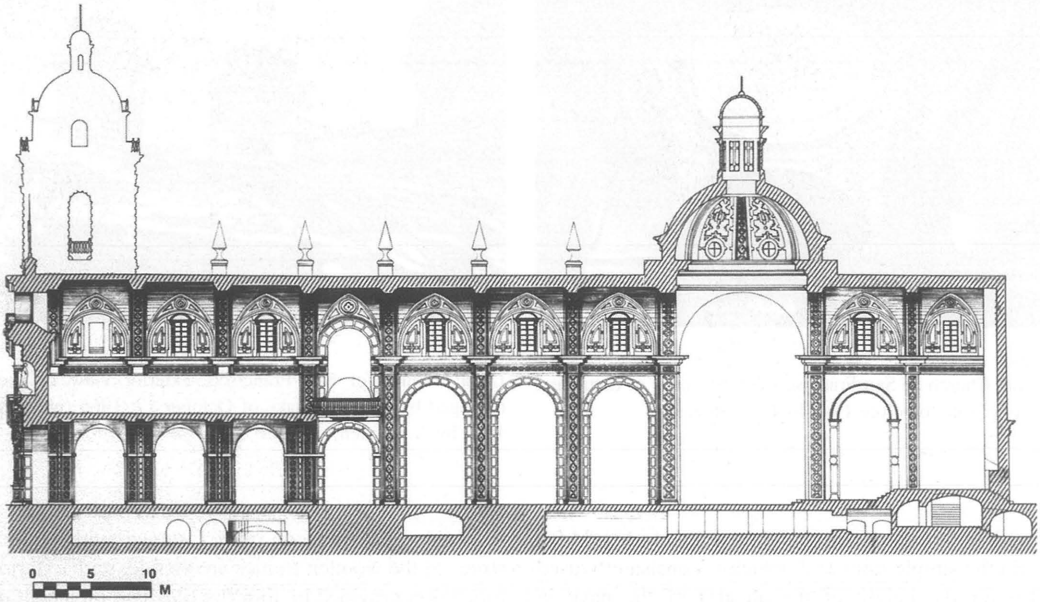


Figure 8
Lima: Church of San Francisco, longitudinal section (after H. Rodríguez-Camilloni and V. Pimentel Gurmendi)

of the intrados (excluding the lantern) dominates the interior space focusing attention on the transept and the apse with the main altar (Fig. 5). It is in itself a remarkable *quincha* structure, carefully designed with the earthquake problem in mind. The section drawing (Fig. 8) reveals it is actually a double-shell dome, with a different interior and exterior profile. Internally, the dome describes a perfect hemisphere supported on pendentives, whereas in the exterior the dome projects a massive though somewhat shallower shape resting on a cylindrical drum pierced with round windows. A greater stability was thus assured, since the exterior drum provides continuous buttressing at the critical points where the lateral thrust is most accentuated. The geometric vertical bands that cover the interior surface contributing to emphasize the effect of verticality, actually locate some of the internal wooden ribs; and small «dots» that form part of the geometric ornament are in fact pegs that help attach the stucco to the structural frame.

The design of the wooden structural frame of the dome may have been derived from the models in De L'Orme's treatise *Nouvelles Inventions pour bien bastir* (Paris, 1561), where a method of dome construction is described as follows:

> It is a very simple method, and of great use in domes, even of large diameter, the principle being that of making the several ribs in two or more thicknesses, which were cut to the curve in lengths not so great as to weaken the timber, and securing these well together by bolts or keys, and observing especially to break the joints of the several thicknesses.[15]

De L'Orme's detailed drawings (Fig. 9) also show how the wooden ribs had to be attached to the masonry structure. However, it would have still been necessary for Vasconcelos and Escobar to adapt this structural frame to *quincha* construction. And the success of the Franciscan model made the *quincha* dome the universally adopted solution throughout the Peruvian coast from the middle of the seventeenth century onwards. Other notable examples included the main dome of the church of Santo Domingo in Lima, rebuilt by the Dominican architect Fray Diego Maroto in 1678–81; the dome of the *camarín* of the

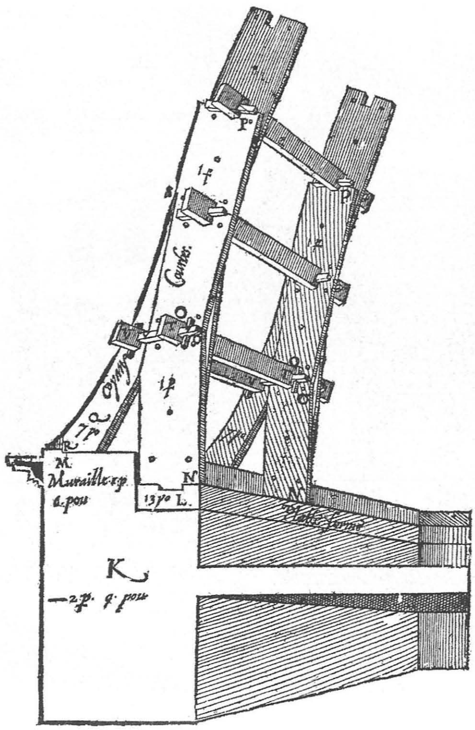


Figure 9
Philibert De L'Orme: Dome construction detail from *Nouvelles Inventions pour bien bastir* (Paris, 1561)

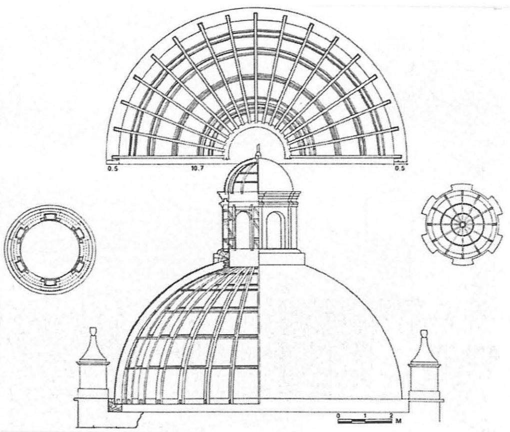


Figure 10
Trujillo, Peru: Church of San Francisco, rebuilt after 1619, analytical drawing of dome *quincha* construction for restoration project following earthquake of May 31, 1970 (after UNESCO-CRYRZA)

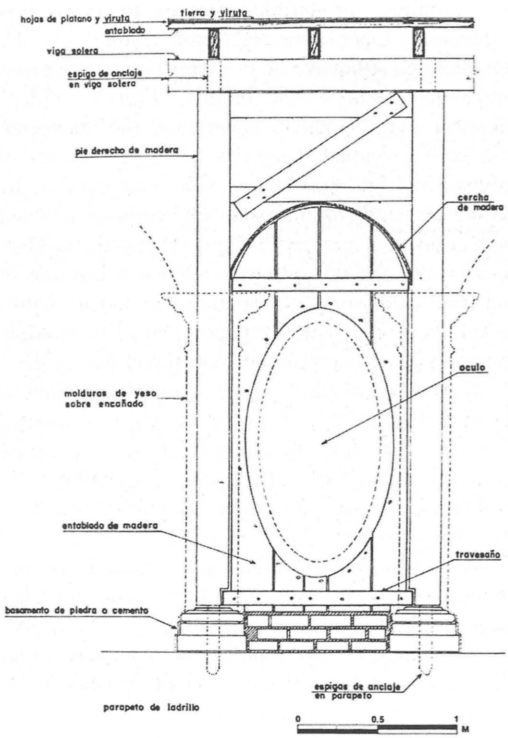
church of La Merced in Lima of 1774, a design attributed to the viceroy-architect don Manuel de Amat y Junyent (1704–1782); and the dome of the church of San Francisco in Trujillo, rebuilt after 1759 and badly damaged in the earthquake of 1970 (Fig. 10). Turning attention to the main cloister of San Francisco (Fig. 11), one of the glories of Spanish colonial architecture in Lima, yet another challenge that confronted architects since the beginning of the beginning of the seventeenth century can be examined. The problem here consisted in designing an earthquake-proof two-story elevation with open arches carried on piers or columns. According to the Augustinian chronicler Antonio de la Calancha, even iron tie bars had been tried in the principal cloister of San Agustín, but all in vain.[16] Repeated failures had shown the imprac- ticality of using stone or brick as a building material in the second story arcades, as had been done in the Franciscan cloister dating from c. 1629. But when the decision was made to rebuild the church of San Francisco in 1657, and it became necessary to rebuild the second story of the main cloister, a new design that has also been attributed to Vasconcelos was used. As a result, the newly developed system of *quincha* construction was adopted for this part of the monastery, accommodating the elegant design of round arches and oval openings which may have been inspired by Sebastiano Serlio (Fig. 14) and can still be seen today. Yet another contemporary engraving by Nolasco provides irrefutable evidence that this was the original design of the cloister as rebuilt during the seventeenth century.[17] The brick arches and corresponding brick and adobe peripheral walls of the ground level (Fig. 11), on the other hand, date from the 1620s, when Bernabé Cobo witnessed the construction of «a new cloister.»[18] Conclusive proof of this fact is afforded by the mural paintings that were discovered in 1974 above the revetments of Sevillian tiles (*azulejos*) that decorate the galleries.[19] These paintings, of exceptional artistic quality, appear to date from the beginning of the seventeenth century and almost certainly can be attributed to an Italian artist belonging to the circle of Bernado Bitti

Figure 11
Lima: Main cloister of San Francisco, panoramic view (photo by Guillén)

(1548–1610), Mateo Pérez de Alesio (1540?–1632?) or Angelino Medoro (1565–1631?). The implications of this important discovery are also significant for the chronology of the church rebuilt by Vasconcelos, because it shows that the dimensions of the nave were already fixed by the pre-existing southern wall of the cloister which had to be incorporated in the new building (Fig. 4).

Thus the designers' major problem in the main cloister of San Francisco consisted in adding a second story that would achieve a satisfactory structural and stylistic integration. How this was done can be best illustrated with the help of analytical drawings (Figs. 12 and 13): On the outside, a light structure of wood, cane and plaster was effectively anchored in a brick parapet raised above the existing arcade; while the lateral bracing to the interior walls and roof consisted of wooden beams and joists. This solution provided a unified structural system which minimized the loading over the existing masonry structures with the desired flexibility. Furthermore, the adaptability of *quincha* construction to an intricate design with rich ornamentation in high relief was fully demonstrated.

Measurements taken of the *quincha* elements in the Franciscan cloister before and after the earthquake of 1974[20] permit a better appreciation of the structural behavior of the system. In most cases, the tendencies of deformation appear to have been accentuated because of the deterioration of materials across time and a general lack of maintenance, particularly during the twentieth century. The degree of deformation of the arcades, with a pronounced outward bulging in their center points, may also be seen in direct relationship to the rigidity provided by the structures surrounding the cloister. For example, the southern side corresponding to the church has experienced the least distortion. In contrast, the western side that has also suffered from high percentages of water infiltration affecting the stability of the foundations and structural piers, the vertical and horizontal



Fiura 12
Lima: Main cloister of San Francisco, analytical drawing of wooden framing of upper story arcades (after H. Rodríguez-Camilloni and V. Pimentel Gurmendi)

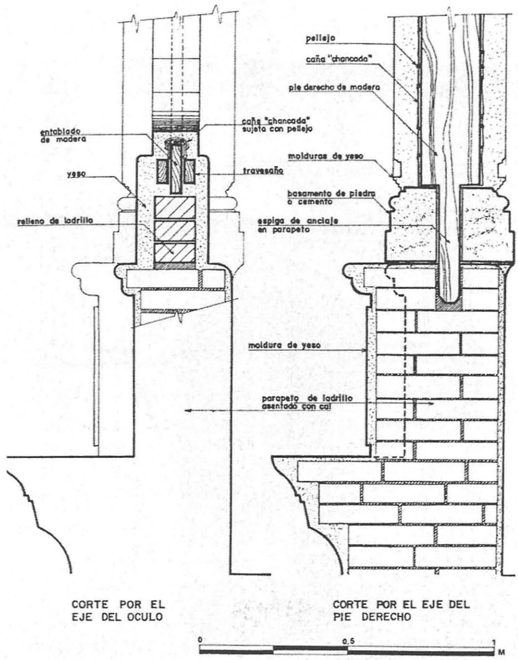


Figure 13
Lima: Main cloister of San Francisco, section drawing showing anchoring of *quincha* structure of upper story arcades (after H. Rodríguez-Camilloni and V. Pimentel Gurmendi)

deformation has been the most acute. Fortunately, a restoration project has been implemented in recent years to save the Franciscan cloister and protect it from future deterioration.[21]

The main cloister of San Francisco had a decisive influence on other Lima cloisters. The tripartite motif consisting of a semicircular arch flanked by two oval openings became a favorite model for other designs (Fig. 11). For example, it was used in the second story of the main cloister of Santo Domingo (Fig. 15) when it was rebuilt in 1678–81; and again in the «Cloister of the Doctors» of La Merced, completed around 1680. Recent research has revealed that Vasconcelos and Escobar also worked on the Mercedarian cloister between 1662 and 1668; and it is possible the work completed in the later date may have followed their original design.[22]

Indeed, the collaboration between Vasconcelos and Escobar may have extended back in time more than is known today; and it was certainly not restricted to the church of San Francisco and the Mercedarian cloister. On March 22, 1668, for instance, Escobar signed in Lima another contract to build the church and convent of the Amparadas de la Purísima Concepción (today Santa Rosa de las Monjas), «according to the plans made with the approval and consultation of don Constantino de Vasconcelos.»[23] The document makes it clear that the Portuguese architect had designed the building, and that Escobar had copied this design on paper in order to execute the work. Luckily this plan signed by Escobar has survived; and there can be no doubt that *quincha* construction was used here also, since the specifications indicate that the barrel vault of the church was to be made of oak frame, cane fill-in and stucco finish imitating masonry work («yeso,

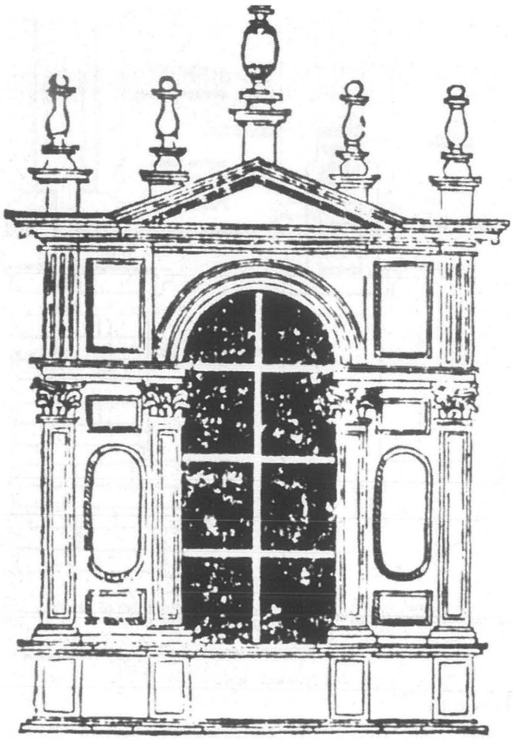


Figure 14
Sebastiano Serlio: Window design from *Libro VII*, «Delle finestre» (Vicenza, 1618)

cañas y cerchas de roble que parezca bóveda de albañilería»). When the church and convent of Sanat Rosa de las Monjas was built on this same site in 1704–08, the new buildings appear to have incorporated, at least in part, the original plan of 1668.

Constantino de Vasconcelos and Manuel de Escobar forever changed the course of the development of Spanish colonial architecture along the Peruvian coast as time would prove the efficacy of *quincha* construction against earthquakes. The fact is that following the severe earthquake of October 20, 1687, the viceroy Conde de la Monclova ordered that no more tall houses should be built in Lima with adobe and brick; and those that would be built were to use *quincha* construction (*telares de madera*), indicating that severe penalties would be applied to any architect or builder failing to obey this regulation.[24] Later in the eighteenth century, after the devastating earthquake of 1746 this prescription won the endorsement of the eminent French military engineer Louis Godin.[25] Throughout the nineteenth and early twentieth centuries, as many houses in downtown Lima still show, walls continued to be built with wooden frames and bamboo in-fill covered with a layer of mud with gypsum or cement. Over these walls, the typical roof included a layering of materials consisting of supporting wooden beams, wood sheathing, building paper, earth-fill, building paper again, and a final coat of gravel and asphalt. And even today, the use of «improved» *quincha* construction continues to be seriously promoted through popular self-help housing manuals distributed by the Peruvian government in collaboration with the international Intermediate Technology Development Group (ITDG).[26]

As the late architectural historian Harold E. Wethey pointed out in 1949, «the important new direction taken by seventeenth century architecture in Lima came with the rebuilding of the church and monastery of an Francisco . . . the decision to adopt imitation barrel vaults constructed of cane and plaster was decisive. This expediency solved the problem of the earthquake-ridden city, and thenceforth no attempt was made to employ heavier materials.»[27] Indeed, Vasconcelos and Escobar's antiseismic system of construction became so widespread during the eighteenth century, that even the Gothic ribbed vaults of the Cathedral of Lima were rebuilt with *quincha* after the great earthquake of 1746. No wonder the seventeenth century historian Fray Antonio de Lorea had once praised Vasconcelos for his «genius and exceptional virtue»;[28] while the viceroy don Melchor de Navarra y Rocaful recorded in his *Memoria de Gobierno* of 1687 that Escobar was «a first rank architect of this city, worthy of recognition among the best in Europe».[29]

Notes

1. In this regard, the following pioneer studies may be cited: Harold E. Wethey, *Colonial Architecture and Sculpture in Peru* (Cambridge, 1949) remained ambivalent about *quincha* construction (which he does not refer to by name), even though he recognized the importance of the church of San Francisco in Lima in

Figure 15
Lima: Main cloister of Santo Domingo, lower story, 1590–1594; second story arcades remodeled, 1678–81; and rebuilt in 1756

this context (see note 27 below). Lamenting the fact that Lima builders had not adopted as a standard solution to the earthquake problem the use of paneled wooden ceilings of Renaissance or *mudéjar* type, he stated: «Instead imitation barrel vaults of wood or of cane and plaster became the rule through out *limeño* churches from the mid-seventeenth century thereafter. Today every church in Lima has imitation vaulting and the effect is in most cases highly unsatisfactory» (p. 73). Pál Kelemen, *Baroque and Rococo In Latin America* (New York, 1951) limited himself to pointing out the «early specimens of cane and plaster vaulting» (p. 152) in the interior of the church of San Francisco in Lima. Brief but more specific references to *quincha* construction are found in Enrique Marco Dorta, *La Arquitectura Barroca en el Perú* (Madrid, 1957), p. 7: «En la costa . . . la necesidad de defenderse de los frecuentes terremotos, impuso las construcciones ligeras y elásticas, a base de estructuras de madera con muros de cerramiento de adobe o ladrillo, bóvedas y cúpulas de «quincha» —cañas y barro—y decoraciones de estuco que, a veces, imitan la fortaleza de la cantería;» and George Kubler and Martín Soria, *Art and Architecture in Spain and Portugal and their American Dominions 1500–1800* (Harmondsworth, 1959), p. 83: «On the arid Peruvian coast, the same menace [of earth quakes] was met at Lima by light and elastic construction of plastered reeds on wooden frames (*quincha*).»

2. Archivo del Cabildo Eclesiástico de Lima, *Obra de la Catedral*, I, «Autos y Pareceres en Razón del Daño Que Hizo en la Iglesia Mayor desta Ciudad de los Reyes el Temblor de 19 de octubre del Año 1609 y el Remedio que se debe tener para la continuación de la obra» (1609–1615). In January of 1615 the *maestro mayor de la Catedral*, Juan Martínez de Arrona declared that Gothic ribbed vaulting should be used in the Cathedral because «[. . .] por la experiencia [los arquitectos] saben que la obra de crucería es la mejor, como se ve por el mucho tiempo que há que se hicieron la Capilla Mayor y crucero, con las demás capillas hornacinas del Convento del Sr. Santo Domingo, y haber pasado por ellas el temblor grande del año de [mil] quinientos y ochenta y seis, y los que más ha habido, sin recibir daño porque son de crucería.»

3. See Humberto Rodríguez-Camilloni, «Constantino de Vasconcelos» in *Encyclopedia of Latin American & Caribbean Art* (London, 2000), pp. 682–683. Abundant biographical information on Escobar may be found in Emilio Harth-Terré, *Artífices en el Virreinato del Perú* (Lima, 1945), pp. 199–222.
4. Recent archaeological work at Caral in the Supe river valley of the northern coast of Peru dating from 3000–1500 B.C. has revealed one of the earliest examples of *quincha* wall construction. Cf. Ruth Shady Solís, *et.al.*, *La Ciudad Sagrada de Caral-Supe* (Lima, 1999).
5. Bernabé Cobo, *Inca Religion and Customs*, English trans. by Roland Hamilton (Austin, 1990), pp. 190–191.
6. Cf. Volker Hartkopf, *Técnicas de construcción autóctonas del Perú* (Washington, D.C., 1985), p. 124.
7. Fray Miguel Suárez de Figueroa, *Templo de N. Grande Patriarca, San Francisco de la Provincia de los doze apóstoles de el Perú en la Ciudad de los Reyes arruinado, restaurado, y engrandecido de la providencia Divina,* published together with *Visita y declaración que hizo el P. Fray Juan de Benavides, ministro legal y honesta persona del Santo Tribunal de la Inquisición y sacristán mayor del Convento Grande de N.P.S. Francisco, en la residencia del Rmo. P.D. Luis Zerbela, padre perpetuo de la Provincia de Santiago, y de todas las del Perú, del tiempo que fue comisario general de ellas* (Lima, 1675), f. 4v.
8. Fray Miguel de Aguirre, *Población de Baldivia, Motivos, y medios para aquella fundación . . .* (Lima, 1647), ff. 35v.–36.
9. Archivo General de la Nación, Lima, Marcelo Antonio de Figueroa, Escribano Público, Prot. 631, Lima, 14 de junio de 1659, ff. 2300–2301v.
10. Suárez de Figueroa and Benavides, *op. cit.*, reproduced in Humberto Rodríguez-Camilloni, «El Conjunto Monumental de San Francisco de Lima en los Siglos XVII y XVIII,» *Boletín del Centro de Investigaciones Históricas y Estéticas*, Universidad Central de Venezuela, Facultad de Arquitectura y Urbanismo, No. 14 (Caracas, septiembre 1972), pp. 42–43.
11. Suárez de Figueroa, *op. cit.*, f. 12.
12. The majestic interior of San Francisco led the late Peruvian art historian Jorge Bernales Ballesteros, *Lima, la Ciudad y sus Monumentos* (Seville, 1972) to label the church the key example of «the great *limeño* Spanish colonial baroque [architecture].» However, it is important to note that all the significant spatial relationships of the interior are governed by classical proportions.
13. Humberto Rodríguez-Camilloni, «Forma y Espacio en la Arquitectura Religiosa de la Capital del Virreinato del Perú Durante los Siglos XVII y XVIII,» in *Arquitectura Colonial Iberoamericana*, E. Armitano, ed. (Caracas, 1997), pp. 287–318.
14. See in particular San Nicolás' drawing for the wooden frame of a cupola on an octagonal drum reproduced in George Kubler, *Arquitectura de los Siglos XVII y XVIII, Ars Hispaniae*, XIV (Madrid, 1957), Fig. 107, p. 78.
15. This is an excerpt of De L'Orme's text as summarized in English translation by Joseph Gwilt, *The Encyclopedia of Architecture* (London, 1867), p. 612. For the widespread use of De L'Orme's method of dome construction in North America during the late eighteenth and early nineteenth centuries, see Douglas Harnsberger, «In Delorme's Manner,» Association for Preservation Technology, *APT Bulletin*, XIII, No. 4 (1981), pp. 1–8.
16. Fray Antonio de la Calancha, *Chronica Moralizada del Orden de S. Agustin en el Peru*, I (Barcelona, 1638), p. 250.
17. This engraving is also reproduced in Rodríguez-Camilloni, «El Conjunto Monumental de San Francisco de Lima,» *op. cit.*, p. 42.
18. Bernabé Cobo, *Fundación de Lima* (1629) in *Obras del Padre Bernabé Cobo* II, *Biblioteca de Autores Españoles*, XCII (Madrid, 1964), p. 421.
19. Fully documented in Humberto Rodríguez-Camilloni and Víctor Pimentel Gurmendi, *Proyecto Integral para la Conservación-Restauración y Adecuación Museológica del Conjunto Monumental del Convento e Iglesia de San Francisco de Lima*, unpublished restoration project (Lima, 1975).
20. *Ibid.*
21. This work, completed in 1989, followed the specifications in Rodríguez-Camilloni and Pimentel Gurmendi, *op.cit.*
22. Cf. Antonio San Cristóbal, *Arquitectura virreynal religiosa de Lima* (Lima, 1988), pp. 316–319.
23. Archivo General de la Nación, Lima, Andrés Roncal Pimentel, Escribano Público, Prot. 1682, Lima, 22 de marzo de 1668, ff. 188–192v. A copy of the original ground floor plan signed by Manuel de Escobar is attached.
24. Archivo Histórico de la Municipalidad de Lima, *Libro I de cédulas y provisiones* (1568–1781), f. 101. The document in question corresponds to a proclamation by the viceroy Conde de la Monclova dated 1699.
25. Archivo General de Indias, Seville, Audiencia de Lima, leg. 511, «*Testimonio de los Autos Seguidos en el Supremo Gobierno del Perú, sobre la Reedificación de las Casas Altas Arruinadas en la Ciudad de Lima, con Ocasión del Terremoto Acaecido el Año de 1746.*»
26. Intermediate Technology Development Group, *Construyamos con Quincha Mejorada* (Lima, 1993).
27. Wethey, *op. cit.*, p. 17.
28. Fray Antonio de Lorea, *Santa Rosa, . . . Historia de su admirable vida y virtudes* (Madrid, 1671), f. 7.
29. Manuel A. Fuentes, ed., *Memorias de los Virreyes que han gobernado el Perú durante el tiempo del Coloniaje Español*, II (Lima, 1859), p. 372.

H. P. Berlage and Amsterdam Stock Exchange, a reflection on the meaning of Construction

Ana Rodríguez García

The appearance of new building materials and methods at the end of the 19th century brought about a profound change in Architecture which, together with other factors, crystallised into the Modern Movement at the beginning of the 20th century. During this transition period, in which traditional and new systems coexisted, an eclectic architecture with uneven results was produced. It was a time of searching when a generation of masters, Otto Wagner (1841–1918) in Austria, Peter Behrens (1868–1940) in Germany, August Perret (1873–1954) in France, or H.P. Berlage (1856–1934) in Holland, among others, faced a new situation. As compared to the past, the architect had to determine and define the use of materials and their relation to new systems of construction, choosing from among a wider array of possibilities than had ever been seen before.

The work of Hendrik Petrus Berlage (Amsterdam 1856–The Hague 1934) is a constant search. Starting with the principle of constructive sincerity and clarity, it marks the beginning of a renovation in Dutch architecture, and by extension a prelude to subsequent vanguards. Berlage became a fundamental figure, not just as the author and builder of magnificent architecture, but also as an element of transition between the 19th and 20th centuries, who drew on the essence of tradition and yet extolled an architecture stripped of superfluous ornamentation.

From among the diverse contributions of Berlage, I will study, through the Amsterdam Stock Exchange building, the construction options employed and the way of using materials, as compared to the traditional way of building, and which will become a precedent for subsequent methods.

Because of its apparently medieval aspect, in some cases, the Stock Exchange has been undervalued for being old-fashioned, though at the time it was controversial for just the opposite reason. It provoked a strong reaction in society because of its supposedly industrial or harsh appearance at the same time that it ended up influencing subsequent generations of architects. In many ways, it is a modern building built with traditional materials. It was not built by wrote. Rather it was the result of a profound reflection and investigation into the meaning of building, arriving at formal solutions based on fostering the building's constructive and structural aspects. It became a manifesto of a certain attitude to uphold in Architecture, which has influenced architects since Mies Van der Rohe and continues in force today.

The Amsterdam Stock Exchange in the period 1898–1903. Analysis of the construction process based on the photographs of the Berlage Archive in the NAi

Subject and scope of the study

This study focuses on the period between the years 1898 and 1903. It is a specific and delimited period that begins with the presentation of the third project in 1898, on which the construction was based, and ends in 1903 with the completion of the building.

The information consulted in the NAi dates up until this year. The information from the following period between the years 1093 and 1911 was found in the Municipal Archive of Amsterdam.

The initial approach of this study was to analyse the photographic and graphic documentation from this period. However, the handling of this documentation, its classification and the crossing of data proved to be a much more laborious process than was expected at first glance.

For this reason, and although the plans and the images were viewed in parallel, in order to achieve a homogenous result within the reasonable scope of this study and not render a partial or incomplete vision of the series of plans from 1898, which were essential to the development process of the building, this study focuses on the photographic documentation.

In this case, the decision to work from the images instead of the plans is based on various motives.

Although some of the images have on occasion been published in isolation, in general they are a source of information that is less well known that the plans, which have been circulated more. At the same time they are interesting in that treated as a whole they provide a novel vision and constitute a document which by itself explains the constructive process.

Of the publications that exist on the building, there are a significant number of photographs of the Stock Exchange. However, up until a few years ago, the images of the construction phase tended to be limited to the publication of one or two given images. Since the end of the nineteen nineties, the books published on the building have begun to include different photographs of the construction. Upon seeing the potential of these images and in looking at them more closely, their quality and preparation stands out. This fact, together with the meticulousness of Berlage's work, leads one to believe, almost with certainty, in the existence of more photographs of the building under construction. These photographs would allow for a direct approach to the issue and, in a way, though the eyes of the architect.

Sources consulted. Original documentation in the Berlage Archive of the NAi

The Dutch Institute of Architecture in Rotterdam, known as the NAi (Netherlands Architectural Institute), houses one of the most important museums of collections and archives on architecture in the world, especially for the period 1880 to 1940.

The Berlage Archive contains the largest portion of the documentation that exists on the work of H.P. Berlage (graphic and photographic documentation, writings, letters, participation in conventions, etc.)

In the case of the Stock Exchange, it contains the graphic documentation from the period of its inauguration in 1903. This documentation includes representative drawings of the Stock Exchange of Berlage and other architects, sketches drawn in different sizes and on different types of paper, plans developing the work, detail and construction plans, and complete series of plans of the different phases of development of the project.

The enormous amount of information that exists explains the constant search and work of Berlage during the complex development process of the building, from its beginnings until its completion. In addition to the drawings from the competition and the projects, there are complete series of perfectly drawn plans of floors, elevations and cross-sections. These plans reflect the variations to the building which in some cases, such as the tower, were further developed during the construction process.

In all cases, the different types of plans express the meticulousness as well as the purposefulness in the drafting the documents. The graphic documentation, which is well organised in the archive, allows one to see the differences in approach, graphics, scale, ways of delimiting and representing between the general plans developing the project and the detail and construction plans.

Surprisingly, in contrast to the ordering of the graphic documentation, the photographs apparently do not have a clear order of classification within the archive. In fact, the original photographs related to the construction of the Stock Exchange are dispersed and mixed together with others in the different boxes containing photographic documentation.

Once the investigation and recompilation work was completed, the hypothesis was confirmed, that like the rest of the documentation, the photographs were taken with a vision of the whole which would explain the different construction phases, although they were not later reproduced as whole.

Method used in analysing the images

The method used in analysing the images consisted in

- — Establishing a first hypothesis regarding the chronological order of the images.
- — Situating them on the building, over the floors corresponding to the 1898 plans.
- — Analysing each image individually.
- — Comparing the set of images.
- — Establishing some general conclusions.
- — Analysing the established order again and reordering.

Carrying out the process of analysing the images allowed me not only to obtain information about the construction of the building, but also to reach some conclusions about the analytical process itself.

The result proved more complex than expected. Just ordering the photographs and situating them on the building was a job that I had to revise and modify several times, and which depended a great deal on the image. Thus, the most simple images were those taken at the beginning or the end of the construction, while the ones taken in between provided more information and were more difficult to understand.

The chronological order cannot be strictly followed. Because of the size of the building and its construction process, photographs taken on the same day may show images of different phases of the process. At the same time, respecting the chronological order, one can obtain different results depending on whether the photographs are ordered by parts or according to the building as a whole.

The images provide information at different levels.

a) Individually and as a whole.
b) From the description of the information about the construction.
   - — of the general process of construction and the order of the different works.
   - — of the means and systems used at the time.
c) From the interpretation of other types of information.
   - — Deliberateness of the image, composition, framing, etc.

Analysis of the images.

The images reveal a clear and planned organisation of the works.

The Stock Exchange was built floor by floor at a roughly even pace although the works began at Dam street and there was a slight longitudinal progression in the erection of the building, starting at Dam street and advancing toward Beursplein street. This permitted work to be carried out at the same time on different sites. This was the system used to raise the main bricklaying and masonry work, place the metallic beams and ties of the flooring. This structure was held without beam filling until the end when the building was covered with the assembly of the roof. The foundations, even though they began at Dam, could have advanced more cross-wise from the street behind toward Damrak.

In Image 4, the works advance from the Dam in the background where we can already see the wooden structures for erecting the pillars of the ground floor on the first shared base with a temporary scaffolding for working. In the middle ground, they are about to finish laying the metallic beam of the floor. In the foreground, we see the area without flooring where they are laying bricks and placing framing for creating the arches. This order is verified in Image 8 where the work advances from the back. We can see the temporary planking for working on the flooring at the same height as the flooring in the foreground. This shows an isolated planking for crossing rather than a continuous work surface. It is also confirmed in Image 10 where from the main hall, we can see the assembly of the exterior structure of the roof of The Passege.

The initial phase on the works began with the driving of wooden piles for the foundations, the bricklaying for the basement and the laying of metallic tie-beams in the flooring of the ground level.

The method used for each of the following floors up to the roof was the following:

- — Erection of wooden structures on the perimeter for scaffolding and preparation of the wooden auxiliary means necessary to erect the pillars or other stone elements and guide the brickwork.
- — Placement of the freestanding stone elements such as pillars with their bases and capitals.
- — Bricklaying with the stonework embedded in

the different levels of the brickwork. The stretches of coloured glazed brickwork are laid at this point as can be seen in Image 8. It is treated not as decoration added afterward, but as an integral part of the brickwork. (In the foreground of this image to the right, we see a wall with a surface of glazed ceramic that will hold a stone corbel which is in turn embedded into the wall).

— Placement of metallic tie-beams in the flooring, waiting to fill in the beams until the end, as can be seen in various photographs, at least in the big halls.
— Laying of the bricks for the vaults and arches.

In the final phase, the beams of the flooring are filled in after finishing some of the decorative brickwork such as the spaced brickwork of balustrades of the upper galleries, the putlogs are closed and other finishing brickwork is done as is the placement of decorative elements, ceramic friezes, and stone bas-reliefs by artists such as Jan Toorop or Roland Holst, in niches made for this purpose in the brickwork.

The auxiliary structures are generally made of wood, except for a few machines and special pieces. They are remarkable because of their extraordinary austerity and simplicity for a work of this size and importance. They are interesting not so much in and of themselves but in the way that they were used to rationally prepare the work sites. In addition to a certain degree of systemisation, they sought to execute the works well. This was particularly important in an architecture without finishing work. Thus, in the areas with groups of pillars or buttresses, before erecting one of them, they prepared the totality of the structures necessary for working on each pillar. In the case of the wooden framework for the repeated arches under a certain size, judging by the quality of their construction and the information provided by Image 4 in which the framework in the foreground is marked with 15M., they appear to have been built in the shop and reused during the work.

CONCLUSIONS

The Stock Exchange is a modern building that was constructed with traditional materials and auxiliary means.

The images of its construction reveal a certain sense of prefabrication, or *clean* work, where traditional bricklaying brought together different types of elements on the site. These elements, such as metallic beams and tie-beams for the flooring or numbered and classified pieces of stone, came finished from the shop.

Bricklaying was the only process that entailed on site *manufacture*, the rest of the elements required *assembly*.

This idea can be seen more clearly in the panoramic images of the work, while the partial views or close-ups show the auxiliary means and works more related to traditional construction.

This sense of prefabrication, which is somewhat different than current prefabrication, was closely linked to the treatment of stone.

Holland is a country without stone. The traditional importance of masonry in construction took on a special relevance in the Stock Exchange because of its prominence in the building and its significance in this country. Images 6 and 7 tell us of Berlage's emphasis on the treatment of this material.

This interest is reflected in the special care taken in its treatment and placement in the work.

The conscientious stonework is simpler in the smaller and repetitive pieces and more complex in the especially important pieces, normally the large ones, such as the big capitals in the series of arches in the main hall, which were finished and prepared to bear the base of up to three different arches on the same piece.

For the construction process, there are a series of construction plans in which the pieces are drawn in their proper location and numbered with alphanumeric codes. This suggests that except for special cases, the pieces were repeated a certain number of times.

The photographs reveal that the pieces arrived at the site after being finished in the shop. The finishing work was different on the visible parts than on the hidden parts although they respect the geometry of the planes and edges. This is because the dimensions anticipate their being fit into the brickwork. Thus in the areas where they come into contact with the brickwork, they came in whole kop and laag measurements. The photographs also show the ordering of the stockpiles, and in some cases we can see the designation of pieces, Image 10.

It is an architecture without finishing work, built according to a philosophy that directly expresses the

essence of the materials. This totally dictated the process of construction and signified a continuous reflection on and investigation of the process itself.

The questions posed and the process of searching for the appropriate solutions, which crystallised in a given formal solution such as the construction of a building, is the essence of the architect's work. It takes on special meaning at a historical time when the conditions and means of construction changed. In this case, the architect finds himself in an unknown situation in which he must search for new solutions.

In the case of Berlage, the search for a new path in Architecture began with how the new and traditional materials were used and their meaning in the final result.

The process began with the Stock Exchange and other buildings from the same period. However, it continued over the course of his entire work, especially with the employment of concrete which he used according to different approaches as shown by the office building of the insurance company De Nederlanden van 1845 and the Municipal Museum of the Hague, his last work.

> It is necessary to understand the material in order to be able to achieve artistic form.
>
> It is probable that reinforced concrete will be the cause of a total evolution in Architecture. It is absolutely necessary for architects to start to study artistic forms if they want to remain masters of their art.

From the speech of Berlage in the International Convention of Architects held in Madrid in 1904, in the section *«The Influence of modern construction processes on artistic form»*.

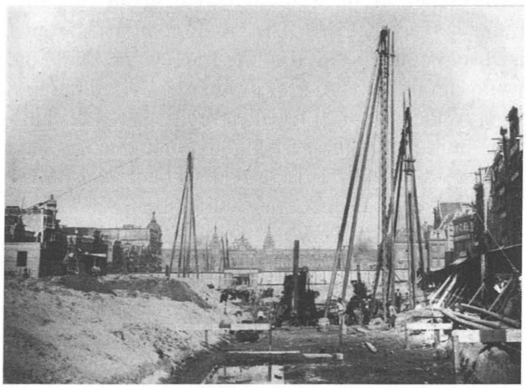


Figure 1

Looking toward Dam street. In the background we see the Central Station building, built in 1886.

Phase of driving the piles of the foundation. Images 1, 2 and 3. The image shows a level at the top of the piles before their heads are joined together below street level.

Earth moving, excavations, and auxiliary elements for on site ranging such as crossbars with levels, 3 the guides without the pile driver, and the second, to the right, wooden structures for driving the piles. Looking at the piles, the one at the rear to the left appears to have been installed recently, the pile driver and the pile are suspended. In the foreground, some workers to the right appear to be plumbing the guides. 2 auxiliary machines, possibly for vertical lifting and pounding of piles with combustion engines.

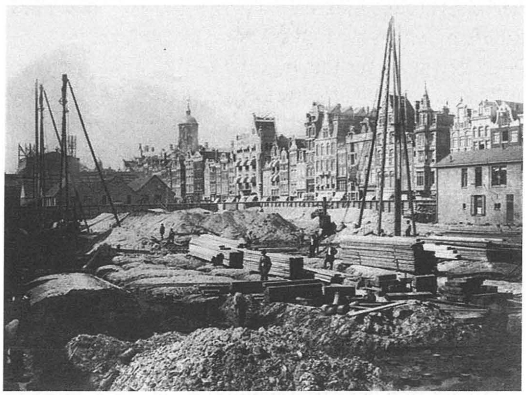


Figure 2

Looking toward Damrak. To the right, we see the Algemeene building, built in 1886, destroyed in a fire in 1960, the department store of C&A currently stands in its place

Perspective is a continuation of Image 3.

Phase of driving the piles of the foundation. Images 1, 2 and 3. The image shows a level at the top of the piles before their heads are joined together below street level, similar to Image 1.

Earth moving and excavations. 3 wooden structures installed for driving piles, the one to the right with guiding tracks, pile-driver and a half driven

pile. 2 auxiliary machines for lifting and driving the pile-driver. In the background and to the right there are warehouse-like buildings that surely existed beforehand and which remain during the works.

With regard to Image 1, there are stockpiles of different types of wood, planks piled for the top level of the foundation, ribbing for this same level and large boards to join transversally various piles. Row of piles and in the foreground an area of piles with water on the surface.

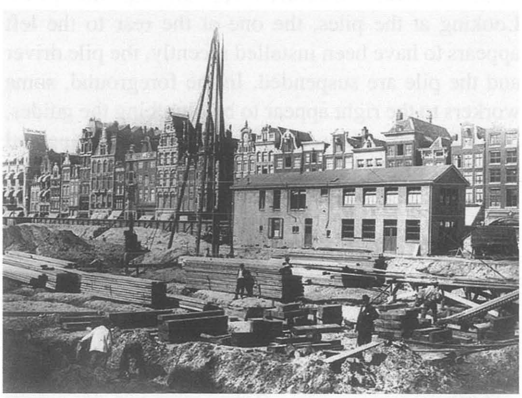


Figure 3

Looking toward Damrak. To the left we see the De Algemeene building, also by Berlage, built in 1886, burned in a fire in 1960, the department store of C&A currently stands in its place.

Perspective is a continuation of Image 2, more to the right. Warehouse-like building that could have existed beforehand and which remains during the works.

Phase of driving the piles of the foundation. Images 1, 2 and 3. The image shows a level at the top of the piles before their heads are joined together below street level, similar to Image 1 and 2.

With regard to Image 1, there are stockpiles of different types of wood, planks piled for the finished level of the foundation, ribbing for this same level and large boards to join transversally various piles.

Row of piles in the foreground to the left where there are two workers.

Looking toward Dam. Perspective similar to Image 1 with the Central Station in the background.

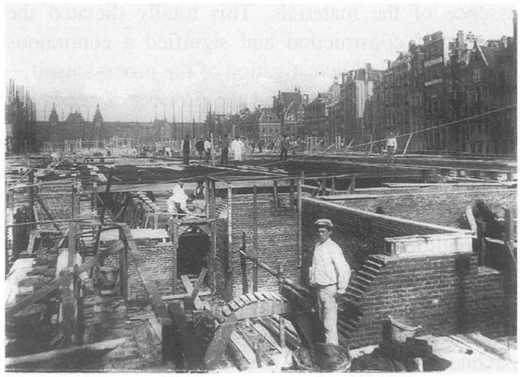


Figure 4

The status of the works corresponds to the basement and the first floor. The works progress from Dam in the background where we see already installed the wooden structures for erecting the stone pillars of the ground floor on top of the first flooring with provisional scaffolding. In the middle ground, the metallic beams of the flooring without an auxiliary floor. In the foreground, an area without flooring where they are laying bricks and placing the framework to form the arches. Stockpiles of bricks under the metallic beams of the flooring. We see also that wooden posts have been installed around the perimeter for the scaffolding.

There are two framework structures prepared for forming arches, and a third one to the left that is on the floor among other materials. Judging by the quality of their construction, they may be reused to form arches in spans of the same width (the first frame is marked 15M). The group in the background is checking the position of the framework, while the worker in the foreground has begun to place the first layer of the arch with bevelled brick. The walls have been built higher on the left where the area has been left free of xxx in order to connect the arch to the wall, which in the upper floors are visually reinforced with a piece of stone which serves as the base for the arches. In the basement, which is for services and installations, stone pieces have not been placed, as we can see from the image.

Looking toward the main entrance on Beursplein street. It corresponds approximately with what we see in the background of Image 4.

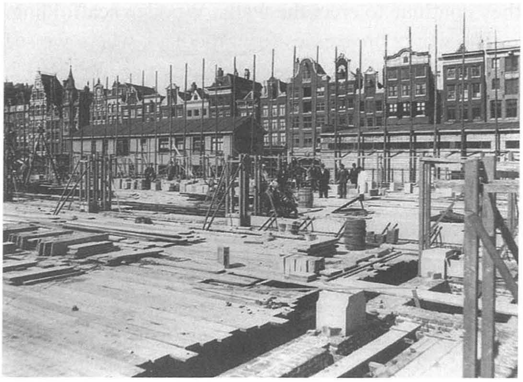


Figure 5

Works on the beginning of the ground floor. First flooring with temporary planking for workmen (in some areas we can see where the metallic beams are embedded in the walls). Preparation of necessary auxiliary measures.

The wooden structures for the buttresses-pilasters of the central wall of the two smaller halls have been prepared. The wooden posts around the perimeter for the scaffolding, and the auxiliary machinery for hauling and lifting have been installed. On this floor, they have begun to place the pieces of stone and we see the first stockpiles.

Importance of the wooden auxiliary means in the placement of stone and in the laying of brick, both visible brick and finishing brick, inside and outside the building.

Looking toward Damrak. To the right we see the Algemeene building, also by Berlage, built in 1886 and destroyed by fire in 1960.

Works on the beginning of the ground floor. First floor with temporary planking for workmen (in some areas we can see where the metallic beams are embedded in the walls). Installation of wooden posts on the perimeter for scaffolding

Stone works and stockpiling of materials.

The main issue of the photograph is the stonework. There are stockpiles of stones and other materials, possibly bricks. They are erecting all elements of the stone pillars-columns (base and capital of softer stone, and shaft of already polished and decorated granite). The stone elements come from the shop totally finished, including the decoration, in which there is a differentiation between the finish of the parts that will be visible and those that will end up embedded in the brickwork. Particularly noteworthy is the stonework on the capitals prepared to support the big longitudinal arches and the smaller transversal arches.

Looking toward Dam, from the perspective of the viewer.

Works on the beginning of the ground floor. First floor with temporary planking for workmen. The wooden posts around the perimeter for scaffolding have been installed. Stone works and stockpiling of material. The image was taken at the same time of the previous one (Images 6 and 7).

Meaning of stone in the building and the importance of the start of construction on the main

Figure 6

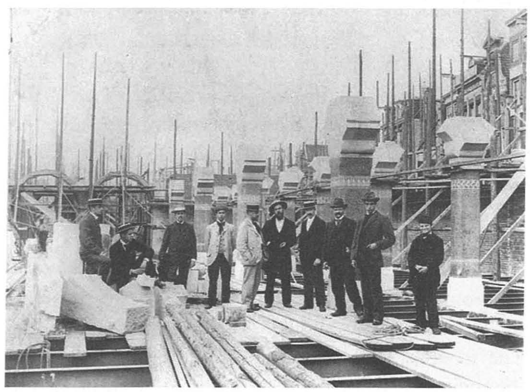


Figure 7

hall. All elements of the stone columns have been erected (base and capital of softer stone, and shaft of already polished and decorated granite). To the left, there stands out in the image a stockpile of stone elements where we see a corbel and we can verify that the pieces arrive finished from the shop, differentiating between the visible and hidden parts.

The presence of Berlage is worth pointing out. He is with a group of people (fifth from the right) who we can assume were close to him. He is slightly in front of the others and is the only person who we see from a profile.

The already explained importance of the stone is linked to the moment and place chosen to take a singular photograph. It is the only one in which Berlage appears in a specially prominent pose. It is the best know photograph from the construction of the Stock Exchange and one of the most published.

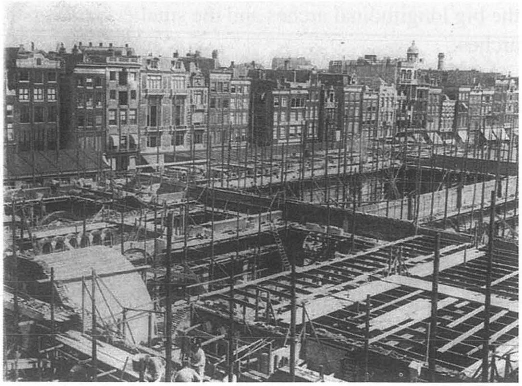


Figure 8

Looking toward the area of Dam street with the Damrak building in the background. Of all the photographs analysed, this is the one that is taken from the highest viewpoint.

Works in the upper portion of the ground floor (depending on the hall) and the beginning of the first floor.

Rooms with lower ceilings already covered with the metallic beams and tie-beams of the floor above. The wooden formwork for the brick barrel vault of the main hall of the central body has been prepared. In the big hall at the back, which has higher ceilings, they continue to erect the walls. Wooden scaffolding.

The works progresses from the back where we see temporary planking for workmen on top of the flooring at the same level as in the foreground. The planking is for crossing and does not offer a continuous surface for working. On this floor, the tie-beams are laid in two continuous sections and are supported in the central area by two joined metallic beams, making the floor look like a single piece. In the central body of the floor, which is more subdivided, to the left we see the upper portion of various arches, some with the framework still in place and the formwork prepared for the vault. Brickworks with two groups of people. In the foreground, to the right, we see a wall with a glazed brick face that is going to support a stone corbel which is in turn embedded into the wall.

Panoramic view from an elevated perspective that allows us to see the relative heights and sizes of the big halls and the rooms with lower ceilings, and understand the special complexity of the building. Different constructive systems such as metallic flooring and brick vaults determine the different character of the rooms.

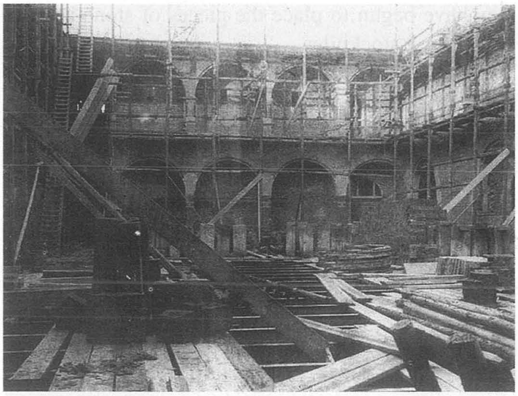


Figure 9

Looking toward the area of Dam street, in the Stock Exchange Hall, now Yakult Hall. This is the first image where although the building has not been covered, we are inside a complete space.

The height of the hall rises up to the level of the first floor, which is the level that supports the metallic

roof trusses. Although it is cut by the cropped in the image, the scaffolding continues higher up, possibly up to the level of the roof, as suggested by the hand ladder.

Wood scaffolding, very high and made of two logs joined end to end, reinforced in some points by diagonal boards. In the upper portion of the wall in the background, the stone columns that bear the arches are still covered by the auxiliary wooden structure used to assemble them.

Stockpiles of stone, brick and different types of wood for auxiliary means (logs, boards, blooms, large boards). The wooden framework for an arch is on the floor.

This is the photograph with the lowest quality and most careless composition.

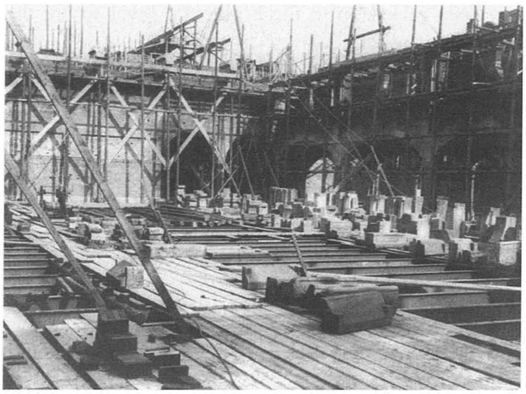


Figure 10

In the main hall of the Stock Exchange looking toward the area of Dam street.

As in the Image 9 before, although the building has not been covered, we are inside a conformed space.

The height of the walls in the biggest hall continues to rise. Beginning of the upper levels. The big lateral arches and the first floor supports have been completed.

The works continue to progress from the area of Dam street. In the background, to the right, we see part of the metallic roofing structure of the Stock Exchange Hall, now Yakult Hall (Image 9). In the wall at the rear, they have begun work on the upper overhanging gallery, with the placement of large corbels of bevelled and protruding stone. Once embedded in the supporting brickwork, they remain propped up at the end until the suspension is completed with a system of vertical logs and diagonal braces in the form of Saint Andrew's cross, which rest on the ground. At the last level of work, auxiliary lifting constructions and on the ground floor, to the left, a cogged wheel machine with a manual crank. Stockpiling of stone elements, to the right, a piece with carved decoration is marked 91 L*A (the asterisk represents a small illegible sign). Other smaller stockpiles of stone, brick and logs for scaffolding. In the lower left hand corner, the board at the end of the flooring is turned upside down and appears to be equipped with small pieces to fit it over the tie-beams and prevent it from sliding along the floor (however, this does not appear in all of them).

In the wall in the background, in addition to the marks from the putlogs, we can see a slightly sunken horizontal rectangle prepared for a later decorative frieze, which will end up flush with the brickwork.

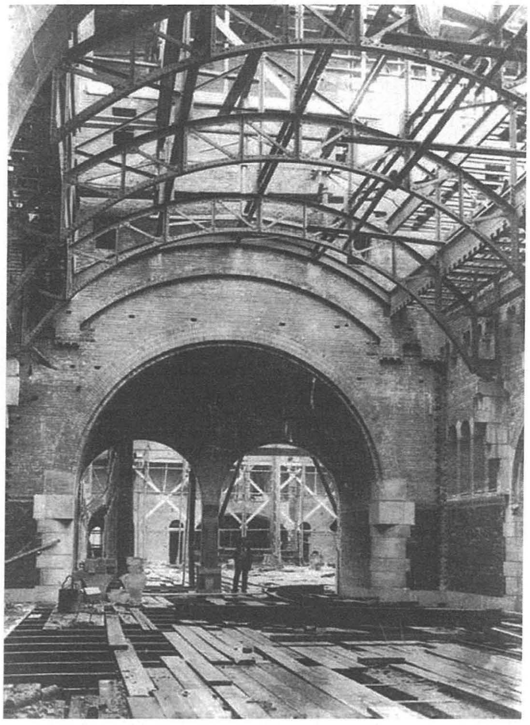


Figure 11

In The Passege, now The Arke Foyer, looking toward the main hall of the Stock Exchange, which can be seen in the background.

We see a structure of metallic roof trusses that have been placed from the interior, and at least part of the exterior of the saddled roof.

The Passege is a hall with a ceiling of uniform height, although it is lower than the other rooms with this type of roof in the central body of the building. It serves as a transition between the two different areas of the building. In the background we see the scaffolding for the series of arches of the main hall.

The roof structure is comprised of different parts. The interior with the lateral horizontal elements which will be covered and the central curved sections which will be transparent. On top, the exterior made of a saddled roof. We see wood logs and planks for the works. Between them, we see two holes in the wall, possibly for access to the inside for maintenance. On the floor, part of the lineal curved elements of the structure and some pieces of stone.

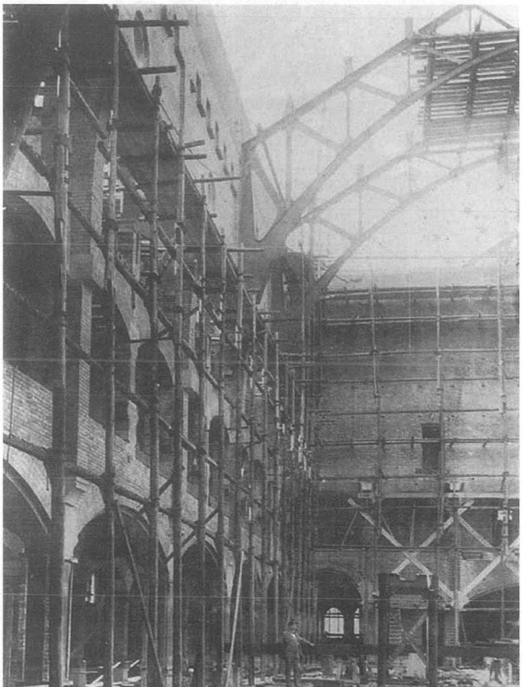


Figure 12

The beams of the floor still have not been filled in. There remain the marks from the putlogs in the brickwork and some corners have yet to be finished.

The double arch at the end of the barrel vault corresponds to the opposite side described in the formwork phase in Image 7.

In the main hall of the Stock Exchange, looking toward the main entrance on Beursplein street.

It can be seen from the previous image, number 11.

We see the placement of the structure of metallic roof trusses has begun seen from the inside.

It is the hall with the most light. It has a roof structure also composed of different parts. Two roof trusses have been placed in the interior structure and there is auxiliary planking for the workmen in the area of the ridge board. On the floor, on the ridges, we see part of one of the elements.

The wall at the rear, the partition walls of the hall, has been raised up to the horizontal level where the slanted plane of the roof trussing structure begins. Here they have continued with the propping system of vertical logs and diagonal braces in the form of a Saint Andrew's cross, and the system of imposing corbels made of bevelled and protruding stone to support the overhanging gallery until it is stabilised by the weight of the wall. The gallery is vaulted for the floor between corbels. Also, we see the marks in the brickwork made for joining the perpendicular walls to the volume sticking out from underneath the gallery.

In the top floors of the lateral series of arches, the balustrades made of spaced brickwork with decoration are missing. The stone bases of these are also missing.

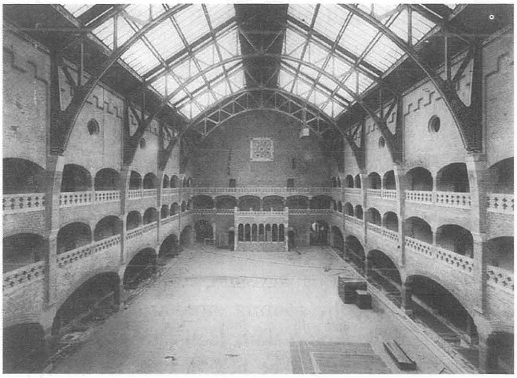


Figure 13

View of the main hall looking toward the main entrance on Beursplein street.

In this hall the works are very advanced.

The roof appears to be finished, even with glass. There is a moving booth suspended from the roof truss at the rear. On the floor there is an area marked off so that the workmen will not walk under the booth.

We cannot see the floor, either because it has not been laid or because it is protected.

Under the series of arches, we see the markings for the installations and on the floor we see rows of stone in the pavement in line with the columns.

There are stockpiles of floorboards and rectangular elements that have been laid down.

The most important panoramic view of the hall in it original configuration. The big arches have not been divided and the trusses do not have braces. These changes were carried out in 1907.

Exterior view of the building with the tower of the main façade toward Beursplein and the western elevation toward Damrak.

We see the building practically finished. They are working on placing the stone bas-relief above the main entrance. Scaffolding and auxiliary work

Figure 14

platform upon which various weighty longitudinal elements have been piled, possibly pieces from the bas-relief as the scaffolding appears to be reinforced. The clock is still missing from the tower.

The perimeter of the work remains fenced off.

Ground floor. Plan from the 1898 series.

Location of the images.

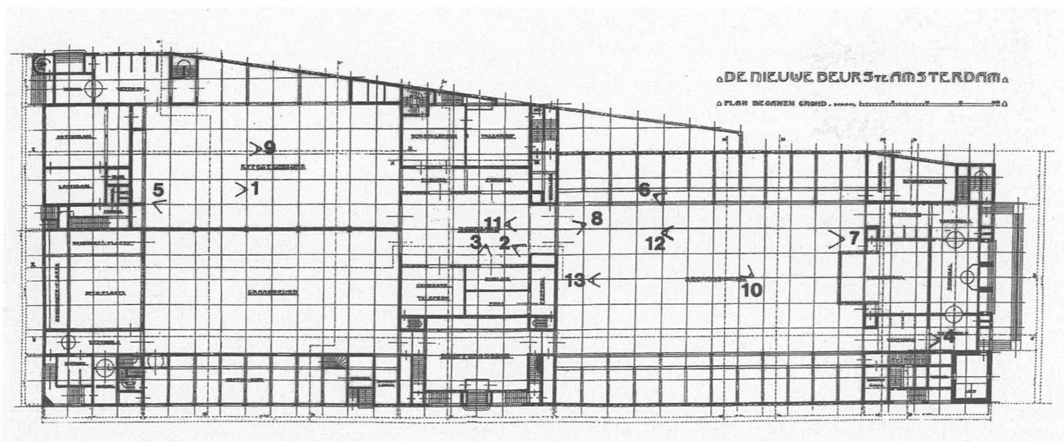


Figure 15

The organisation of civil engineering construction in Britain 1760–1835

Peter Cross Rudkin

The evolution of the organisation of civil engineering construction in Britain to the system which became standard in the later 19th and much of the 20th century was by no means a linear progress. Nevertheless, comparing what existed in 1760, at the start of the Canal Age, with the situation three quarters of a century later when railway construction was starting in earnest, it is possible to see a general shift towards a more professional approach. This paper will look at the way in which the various participants operated in the period 1760–1835.

The client

The first decisions in any construction project, whether and who to appoint as a professional adviser, lie with the client. Before 1760, clients could be categorised broadly as government departments (such as the Office of Works, the Board of Ordnance or Navy Board), local government (magistrates in Quarter Sessions, Commissioners of Sewers, Commissioners of Supply), quasi public bodies (turnpike commissioners, harbour trustees or fen drainage commissioners), joint stock companies (canals), and a few individuals.

Government departments usually employed a large permanent force of craftsmen, who by tradition were employed in new works as well as the repair and maintenance which was their primary role. This privileges, which could carry significant perquisites, was jealously guarded, although on occasion for major works it was necessary to employ outsiders (Colvin et al 1976, 28; Coad 1989, 24).

Much of the work which local government commissioned was traditional in its scope and methods, and well within the capability of the local craftsmen to design and construct. Thus in 1749, the East Kent Commissioners of Sewers decided to «cause a new strong bridge of brick and stone with two arches to be built by John Bundock, bricklayer, of such dimensions and in such sort and manner as are mentioned in his proposals and plan thereof now delivered into court . . . » (Melling 1959, 50). In 1771 John Gethin, a stonemason whose son later became County Surveyor of Herefordshire, contracted to build Lucton Bridge at Mortimer's Cross to his own design and to keep it in repair for seven years, as an implicit guarantee of the adequacy of the design and the solidity of the workmanship (Herefordshire RO: Q/SM/12). (2) In 1802 it was left to the Clerk of the Peace in Northamptonshire to obtain an estimate «from an intelligent workman» for repairs to St Peter's Bridge (Northamptonshire RO: QS Minute Book 1797–1802). Numerous other examples could be cited for, although by 1800 half of the counties of England employed a county surveyor, in 1835 at least eleven of the remainder had yet to make an appointment (Smith 1985, 113–114).

Canal companies usually employed consulting engineers, though as late as 1810 the Stratford on Avon used William Whitmore, a shareholder whose

previous experience was only on the periphery of civil engineering (Skempton et al 2002, 777–778). Most of these consultants held only part-time appointments, so that many decisions were left to be taken on the spot. This enabled the company's committee of management, a small group of active shareholders with delegated powers who quite frequently, to participate directly in engineering matters. The Staffordshire & Worcestershire, one of the first two joint stock canal companies (Harris 2000), did so in 1766 by appointing a member of the committee as Clerk of the Works, with an experienced surveyor as Under Clerk to support him. Decisions on the Leeds & Liverpool in its early years were taken by committee members with the advice of their Engineer, John Longbothom, but in 1775 the Committee met several times and were «unable to give proper directions for the works for want of necessary information from him» (RAIL 846/2/2). (1) Longbothom resigned in July and individual committee members managed the works for two years before promoting one of their inspectors to the post of Engineer (Clarke 1990, 85).

That committee members might have had an inflated view of their capabilities is shown by the saga of the Dudley Tunnel. Working to the design of Thomas Dadford, the initial contractor was the well known John Pinkerton. He was dismissed in1787 after the Company became dissatisfied with the quality of work and rate of progress. A proprietor, Isaac Pratt, was «requested to take upon himself the management and direction of finishing the tunnel and that our Clerk do enter into such contract as Mr Pratt shall direct for the compleating thereof with any person or persons he shall approve of . . . provided that every such contract shall not exceed the space of two years in the performance thereof . . . » (RAIL 824/2). He struggled on for almost three years; the tunnel became out of line and it required a further year and a half under the experienced and competent engineer Josiah Clowes to bring the work to completion.

Similar problems arose in the development of Grimsby as a port. The lay members of the Haven Company resented paying the usual percentage fees to their engineer, and having arbitrarily reduced them, dismissed him. They then proceeded to execute the work under the direction of a local alderman until a series of accidents and changes of plan forced them to call in John Rennie, one of the leading engineers of the day. Work had progressed so far that he was obliged to propose a scheme that was less than ideal. In this case the Company did proceed with the Engineer's plans but it was costly and it was only the arrival of the railway fifty years later that transformed the commercial prospects of the port (Jackson 1971, 14–22).

Inertia could also be a problem. In 1791 «Lord Lonsdale has seen many plans as propositions for the alterations of the harbour of Whitehaven. Not one of them has been approved of by the Trustees or the town. It was his wish that an Engineer should be consulted. With a great deal of trouble and difficulty, he obtained the presence of Mr Smeaton (the first Engineer in the Kingdom) to view and inspect the harbour . . . and the Trustees, totally disapproving of what Mr Smeaton had plann'd and the Trustees not agreeing upon a plan of their own, the harbour remains as it was» (quoted in Scott-Hindson 1994, 30). Poor attendance too could cause a hiatus. The Ashby Canal committee was not quorate several times in 1795/96 (RAIL 803/2) and the Stratford Canal in 1809 (RAIL 875/1).

Sometimes the Engineer had only the appearance of freedom of action. In September 1795 the Salisbury & Southampton Canal ordered contracts to be let «for cutting such parts of the canal as Mr Hill has set out, and in such lengths as Mr Hill shall think most adviseable. It appears to this Committee as if pounds betwixt lock and lock are the lengths most adviseable.» (Southampton RO; D/PM6/2, 52). No doubt he took the hint, only to run into trouble when the Company suffered financial problems and outside consultants were called in to report.

An author writing about turnpike roads in the Edinburgh Review in 1819, eight years after McAdam published his *Observations of the Highways of the Kingdom*, put one side of the argument.

> The causes of this universal mismanagement may perhaps receive some explanation . . . the fundamental principle is always to vest the management in the hands of the country gentlemen; and as they act gratuitously, it has been the policy or the law to appoint in each Act a prodigious number of commissioners —frequently from one hundred to two hundred, for the care of ten or fifteen miles of road; and thus a business of art and science is committed to the discretion of a promiscuous mob of

> peers, squires, farmers and shopkeepers, who are chosen not for their fitness to discharge the duty of commissioners, but from the sole qualification of residence within a short distance from the road to be made or repaired . . . They leave the art and science of the business to their surveyor —who is commonly just as much in the clouds as themselves as to his own proper calling . . . (cited in Hughes 1964, 205)

It should not be thought though that every amateur was incompetent. The Rev. Dr. Henry Beeke was Dean of Bristol and Regius Professor of Modern History in Oxford University and a friend of the owner of Torquay Harbour. It had been built to John Rennie's plan but without his supervision, and suffered damage by storms. Beeke then undertook the direction of the work, made alterations to the plan and brought it to a successful conclusion in 1815 (Russell 1960, 75–76). Malet (1977) has argued for the contributions of the Duke of Bridgewater and his land agent John Gilbert to the construction of the Bridgewater Canal. Nor were the local surveyors always lacking. William Field was a shopkeeper of Cartmel, who became High Constable, Stamp Distributor, Vestry Clerk and Will Maker, and held the office of Bridgemaster to North Lonsdale Hundred of Lancashire from 1816 until his death 44 years later at the age of 91 (Williams 1975, 53).

Nevertheless, the pace of change was increasing. The period from 1690 onwards had been one of increasing trade and prosperity, which provided both the technical challenges to require the services of professional engineers and the continuing employment which enabled a number of men to specialise in this work. Skempton et al (2002) list thirteen such people, not a huge number. From 1760, the number and more particularly the complexity and size of civil engineering projects increased significantly. The average annual value of projects associated with professional engineers in the 1750s was £20,000, in the 1760s £98,000, the 1790s £703,000 and at or near that level thereafter. The number of these major projects started each decade rose from 8 in 1690–1759 to 28 in 1760–1789 and 39 in 1790–1830 (Skempton et al 2002, xviii). Much of the increase in the years 1760–1799 was due to the boom in canal construction. When that gradually tapered off, it was replaced by work in commercial ports and naval dockyards.

Before 1795 new works in the dockyards were initiated by the yard officers, or less usually by the Navy Board. A small department was created for Sir Samuel Bentham as Inspector General of Naval Works, which introduced several important improvements, but the appointment cut across existing lines of responsibility. The Navy Board may have been reactionary but Bentham seems to have been a difficult man to work with, and the former managed to ease him out of office by 1812. (Coad 1989, 23–40) Despite this, his reforms took root, with the employment of full-time surveyors and outside consultants.

Canal companies too could be forced to confront reality. In 1798, five years after having tried unsuccessfully to recruit an Engineer, the Ashton under Lyne Canal minuted «It being the decided opinion of this Committee that the works of the said Canal have been in many instances improperly managed for want of the assistance of a proper engineer and that thereby the interests of the said Company of Proprietors have suffered materially, Resolved that Mr Outram be . . . requested by this Committee to accept the appointment to the office of Engineer . . . » (RAIL 804/1).

By 1835 it was more usual than not to employ a professional consulting engineer to justify the economic benefits, obtain Parliamentary approval, design the works and procure a contractor to execute the design.

The professionals

It should be borne in mind that engineers were not the only professionals involved in the organisation of civil engineering projects. At Westminster Bridge, the largest project in the years leading up to 1760, the Commissioners were appointed under an Act of Parliament. They appointed Charles Labelye Engineer, Richard Graham Surveyor and Comptroller of the Works and Thomas Lediard Surveyor and Agent. The latter two were responsible for measuring the works, keeping accounts and negotiating the purchase of the lands required (Walker 1979, 88).

This division of responsibility by profession is repeated in most of the canal companies whose minutes still exist. At the first meeting of the proprietors, it was usual first to elect a Treasurer, who would collect the capital from the proprietors as calls were made, and provide funds to the labour force or

contractors as work progressed. Next would be the election of a Clerk to the Company, who would keep the legal records and be responsible for reaching agreement with sometimes reluctant landowners for the necessary lands. Only after that came the appointment of the Engineer, usually a part-time appointment.

The Treasurer

Treasurers usually had only an indirect effect on civil engineering contracts. The most common was the consequence of lack of money. In the public service, delayed payment for months or even years by the Office of Works, caused often by unworkable Treasury rules, could cause severe cash flow problems for the contractors. There was an instruction that interest should be paid at 5% on outstanding balances, but this was not always much help (Colvin et al, 93–95).

In local government, justices met at Quarter Sessions four times a year, and it was rare for payments to be made until sanction had been given then. It was not infrequent that amounts were challenged, in which case the total amount might be withheld for a further three or six months. Kirkcudbrightshire even had a standing order that payments would be agreed only at the Easter meeting (Dumfries and Galloway RO: Commissioners of Supply minutes K1/1/3, 19Jun1787).

Canal companies, particularly from 1790 on, were plagued by subscribers who could or would not pay their calls as they fell due. Though often due to unrealistically low initial estimates of cost, this problem could be self-feeding. The Ashby Canal was not atypical when, in 1796 with only 60% of the capital called, it restricted its rate of expenditure and borrowed money at interest (RAIL 803/2). The Worcester & Birmingham was £12,680 in arrears when it was forced to consider suspending work on West Hill Tunnel (RAIL 886/4, 10Nov1796). It was customary to allow interest at 5% on calls paid up, and as the construction period lasted for some years before substantial income could be generated, the outflow of capital could be significant. One shareholder in the Somersetshire Coal Canal in 1802, seven years into the construction phase, paid only £15.93 of the £50 due, the £34.07 being a rebate for interest on earlier payments (Somerset RO: DD/MY/30). In these circumstances, it would have been unwise to enter into large contracts for construction, which the company might have been unable to honour. Several companies, throughout the Canal Age, responded by letting a succession of contracts for short lengths to the same people —the Staffordshire & Worcestershire in the 1760s, the Salisbury & Southampton and the Brecknock & Abergavenny in the 1790s and the Leeds & Liverpool in the 1800s are examples.

On some canals, such as the Grand Junction, the Grand Union and the Pocklington, the Treasurer made over the cash to the Engineer, who then paid the contractors on site. This caused disruption to the supervision and exposed the staff to extra risk, and both the Ashby and the Kennet & Avon had to remind their Treasurer that it was part of their duty (RAIL 803/2, 31Oct1794; RAIL 842/2, 17Oct1796). When the payments did arrive, it was sometimes in an unacceptable form. The Leeds & Liverpool paid their contractors with bills, which could only be cashed at a discount (RAIL 846/4, 12Jul1791). The scale can be gauged from John Upton's claim for £65–10–0 loss on bills for Llanellen and Pant y goytre bridges, contracts worth £3720 in all (Gwent RO: QS minute book 8, 19Feb1827). Even the workmen were not immune. The Monmouthshire Canal paid them two thirds in cash, one third in notes, and on the Basingstoke, the contractor had shilling pieces minted in copper, probably to cover a lack of smaller cash (Holland 1992, 14).

The Clerk

Although the office of Clerk of the Peace was of long standing, and could be considered to be analogous to that of Clerk to the Company, not all canals found experienced people available to serve. The Chester Canal ordered their Clerk to buy a book in which to record their minutes, instead of entering them upon a loose sheet of paper, as there was some question whether the record was being subsequently altered (RAIL 816/2, 25Jun1773). As late as 1795, the Neath had to send their Clerk to the Birmingham Canal to learn about his duties (West Glamorgan RO: D/D Nca84).

On the earlier canals it was part of the Clerk's role to arrange the purchase of lands. The Act usually

forbade a start to be made on the works until the land had been bought, or at least a tender made for its purchase. In 1769 the surveyor of the Staffordshire & Worcestershire was diverted from other duties in order to set out the line of the canal through Kidderminster. The Clerk, a part-time appointee, had unexpectedly come over and «his time was precious». The surveyor did his best to comply, though there obstructions, as failure to do so would have meant the loss of a whole season. (Staffordshire RO: John Green's day book 8). Later, much of this aspect of the work was undertaken by specialist land valuers, such as Samuel Wyatt of Burton on Trent, who acted for the Leicester, Grantham and Nottingham Canals.

The Principal Engineer

The period 1760–1835 saw the establishment of two professional institutions for engineers, the Society of Engineers in 1771 for a few leading practitioners, and the more widely based Institution of Civil Engineers in 1818. The new approach was typified by John Smeaton (Smith 1976, 181) and later his former pupil William Jessop who «considered himself as responsible in point of honour and character for the due execution of the [Cromford] canal» (RAIL 819, 4Nov1789). They tended to be paid at an agreed daily rate or annual salary rather than a percentage of the cost of the works, as architects had been (Coad 1989, 30) and engineers would again be in the future.

These men brought a new awareness of their position to the organisation of their works. Brindley's relations with the academics who formed the committee of the Oxford Canal is well known (Hadfield 1966, 19; RAIL 855/2, 8Aug1769), and Smeaton's views are recorded in his reports (Skempton 1981, 217–219). Rennie wrote of the Directors of the Royal Canal of Ireland «I do not mean to say they should not settle the works of any dimensions most agreeable to themselves, but when that is done, they ought to leave the execution to me, or appoint some person more capable» and insisted on acceptance of his terms before any further work was done (ICE Rennie reports 4, 106). (3) On other occasions he was willing to be guided by clients with specialist knowledge, such as Trinity House, when they criticised his design for a lighthouse on Plymouth Breakwater (ICE Rennie reports 12, 220).

But the Engineer was not yet prepared to act independently in commercial matters. When the design for the lazarette at Chetney Hill was altered to suit the landowners and ground conditions changed, Rennie recommended the Board of Customs to pay enhanced rates for the work but left it to them to decide whether to do so (ICE Rennie reports 6, 225 & 9, 73). Some clients needed advice. When a contractor on the Montgomeryshire Canal claimed extras for cutting feeders to the canal, of which there was no mention in the contract, the Company had to write to the Hereford, Leominster and Ellesmere Canals to ask what their practice was (RAIL 852/11). By 1832 a more modern view was emerging. Sir John Rennie wrote to a resident engineer «I have seen the certificate you have sent for Mr Dyson, but it is by no means sufficiently explanatory . . . send it to me for my approval before granting another certificate, for the greatest precaution will be necessary on your part in order that justice may be done to the Commission and that the Contractor may not be used with undue severity».

The new profession found that demand for competent personnel outstripped supply. The Leeds & Liverpool appointed James Brindley as their Principal Engineer without checking with him first, and when he declined, had to promote the Chief Clerk of the Works to the post (RAIL 846/2/1, 31Aug1770). Later they named Smeaton, Whitworth, Yeoman, Henshall, Tofield, Morris or Jessop as possible consultants, in the hope that one would be available (RAIL 846/2/2, 19Jul1775). The Nottingham Canal appointed Jessop as Engineer to the Company, but then had to ask him on what terms he would be prepared to act (RAIL 854/2, 26Jun1792). The Herefordshire & Gloucestershire, having failed to secure Robert Whitworth's services, instructed Josiah Clowes to apply to Hugh Henshall in Staffordshire, or Thomas Dadford senior if he too was not available (RAIL 836/3, 3Sep1792). On the other hand, the Shrewsbury were turned down by Jessop and Dadford and were fortunate to secure part of Clowes' time (RAIL 868/1, 14Aug1793).

The problem was exacerbated by the difficulties of communication with these peripatetic men. Smeaton explained to the Forth & Clyde Canal that he did not respond to correspondence while he was away from his office near Leeds, as he considered that his proper place for engineering (Scottish RO: FCN/1/2,

29Nov1769). Rennie's travels can be followed by the addresses on the letters he wrote, on one occasion spending two-and-a-half months away, but letters to him often chased one stage behind him, and he too could often not respond adequately until he reached home and could consult his records there. It took six months for him to receive the necessary information and find time from his other commitments to make preliminary designs for Kelso Bridge (ICE Rennie reports 2, 8May1799).

The new professionalism required new procedures to make it effective. For bridgeworks, specifications became longer and more detailed. Tenderers could view these specifications at stated times at the lodgings of the Engineer or the Clerk. Subsequently they were still often written on parchment as part of a single document which formed the contract. At least by 1798, the policy of letting several small contracts on the Kennet & Avon Canal had led to the preparation and printing of a specification which the successful contractor signed. On the Edinburgh & Glasgow Union Canal in 1818, the practice had increased to the extent that each of the contracts had its own printed specification (ICE Telford manuscripts).

Bills of quantities, in all but name, were in use on the Staffordshire & Worcestershire Canal in 1766. There James Brindley drew up a table of rates for excavation which took account of four different types of soil and four depths of cutting. Tenders for canal work usually included different prices for cutting, with extras for depth of excavation or long wheeling, and were measured in linear, square or cubic yards as appropriate. The contract in 1795 for the aqueducts on the south end of the Lancaster Canal had an item for provision of temporary works as well as the more conventional rates for foundations and stonework. By 1811 the Bridgemaster of the West Riding of Yorkshire had printed Bills of Quantities for tenderers to use, from which comparisons could be made (West Yorkshire RO: QD3/367). Similarly, Rennie urged the client at Pembroke Dockyard in 1815 to accept the second lowest tender, basing his argument on a comparison of bill rates.

The use of standard bills also helped to resolve disputes about payment. When Usborne, Benson & Co delivered beech to Chatham Dockyard for bearing piles, it was measured by girth for payment, which Rennie noted was standard practice and well understood (ICE Rennie reports 8, 367).

The site staff

The new breed of principal engineers had clear views on the staff necessary for satisfactory supervision of construction. Smeaton's model is set out in full in Skempton (1981). Rennie took matters further in his report to the Kennet & Avon Canal (RAIL 842/2, 22Jun1795) and Telford on the Caledonian Canal (Penfold 1980, 129–150). Such advice was necessary because the resident engineering staff were almost invariably employed by the client for the works, rather than the Engineer. The appointment was usually full-time, though James Barnes on the Oxford and Grand Junction maintained his business as a brewer and Samuel Hartley on the Barnsley as a maltster.

In the 1760s it was hard to find anyone with the right blend of experience and skill. The Birmingham Canal had two candidates for election as Clerk of the Works, but chose a third. For Under Clerk there were six applicants, and the man appointed was the only one who appears to have made a career in civil engineering (RAIL 810/1, 18Mar1768). The Clerk on the Coventry had to go to the Trent & Mersey for instruction, and his counterpart on the Droitwich to Yorkshire for the same reason (RAIL 818/1, 19Feb1768; RAIL 822/1, 4Mar1768). The Clerk of Works on the Oxford confessed to doubts about the accuracy of his own plans «because of his inexperience in canal matters» (RAIL 855/2, 15Aug1769). Again in the 1790s, the canal mania created a shortage of people and the Gloucester & Berkeley had to choose between two with experience, two with none and a local surveyor. The references for one of the experienced men were unsatisfactory, leaving the committee with little real choice (RAIL 829/3, 15Oct1793).

Later, posts could be filled by personal acquaintance on previous works. Benjamin Davis on the Kennet & Avon Canal was commissioned to approach colleagues on the Basingstoke Canal, his previous employment. Where there was no connection, references could be sought. The Rochdale Canal gave William Crosley junior a satisfactory report when he was appointed to the Brecknock & Abergavenny. The Leeds & Liverpool did likewise for Charles Pickmore, despite having cautioned him for drunkenness shortly before; he did not last long in his new employment at Lancaster.

To find a suitable resident engineer, the Ellesmere Canal placed advertisements in newspapers as far afield as Chester, Shrewsbury, Leicester, Northampton, Coventry, Birmingham and London (twice), only to find the ideal candidate, Thomas Telford nearby in Shrewsbury (RAIL 827/1, 1793). Where the postholder was responsible for handling money, substantial security was required, £5000 in this case.

The Clerk of Works was often required to find his own immediate subordinates, and occasionally his salary was specifically stated for himself and his deputy. Telford, mentioned above, was allowed £300 p.a. for three clerks or superintendents, whom he was to employ. John Longbothom's proposals to the Leeds & Liverpool included for his occasional employment of three or four persons, to be reimbursed by the Company (RAIL 846/2/1, 16Oct1772). When Nicholas Brown was appointed Surveyor, Book Keeper and Superintendent of the Huddersfield Canal, his salary of £315 p.a. was to pay for himself and an assistant, both full-time (RAIL 838). By 1809 the rate for Thomas Cartwright and an assistant on the Worcester & Birmingham Canal was 400 guineas p.a. (RAIL 886/5, 1Mar1809), and by 1830 on the St Helens & Runcorn Gap Railway, Charles Vignoles was paid £650 p.a. for complete design and supervision (RAIL 593/1, 15Jun1830).

The job was not without its financial risks. The Chester Canal, not the easiest of employers, at first required that the contractors' accounts should be certified by the Clerk to the Committee, but then put this responsibility onto the Engineer and ordered that the cost of any work not done properly but certified, should be deducted from his salary (RAIL 816/2, 21Jan1774). The Warwick & Birmingham tried to do the same when it dismissed its Engineer (RAIL 881/7, 14Nov1797).

A more unusual hazard of the job was that which John Thomas encountered at Sheerness Dockyard. He had been resident engineer on this large and difficult job for five years when it was found that public materials had been used for private gain, and the mother of one of the workmen had been placed on the payroll as a millwright. In his report outlining the site organisation required, Rennie had suggested that the resident engineer should not be responsible for payment of wages and that certification of work should done jointly with a dockyard official. Dismissal was contemplated, but his value to the works and lack of personal involvement saved the day (ICE Rennie reports: 9.418). Thomas had worked for Rennie before going to Sheerness, but was employed directly by the client. This was the case with Phillip Richards at Chatham Dockyard also, who found himself in trouble for giving orders varying the contract, contrary to the rules of the naval service, after consulting Rennie but not his employer. He too was a competent and valuable engineer and survived to be promoted to supervise the Royal William Victualling Yard at Plymouth. Engineer' (ICE Rennie reports 14, 25Jan1823).

The contractor

By 1835, most work was undertaken by contractors working to the designs of a consulting engineer, the work having been won by competitive tender. The contractor would require managerial ability to organise the labour, equipment and materials in order to complete the works within the programmed time, to the specified quality and to make a profit. He would also have the financial strength to fund the work in progress, receiving payment up to two months in arrears. The technical knowledge to design the temporary works and uphold the works in an incomplete state was not always required, as their design was still provided on occasion by the consulting engineer.

Contractors with some but not all of these attributes can be recognised well before the period under review. Sir Thomas Fitch was active from 1663 to 1685, and built the Fleet Canal for the City of London in a contract which might be worth £15million today. The emergence of the modern contractor was influenced also by the attitude of the Engineer. Even in 1834, when major new railways were being planned, Francis Giles and Robert Stephenson could take very different views about the size of contract which should be awarded (Parliamentary evidence on London & Southampton Railway). Stated simply, large contracts would attract men of capital, who could manage the interface between the different works; they would also preclude many potential tenderers and therefore lead to higher prices. Events on the London & Birmingham Railway [1833–38] might suggest that the day of the large contract had not finally arrived (Lee 1964, 112).

It has been suggested that the early canal contractors were little more than superior gangmasters (Burton [1972] 1993, 173), and in some cases that was so. In order to reduce the contractor's capital, it was a common practice for the company to supply wheelbarrows and planks for the runways along which the excavated soil was wheeled. Sometimes even the tools were provided. Eventually most companies grew weary of employing a person to keep track of these items when they went mysteriously missing, but even as late as 1834 the experienced William Tredwell was being offered £30,000 of temporary works for a contract which would be worth about £600,000. But the independent contractor was making an appearance. In 1766, John Beswick undertook the whole of the cutting of Kymer's Canal, bringing workforce and equipment to South Wales from the north of England (Bowen 2001, 21) and shortly afterwards undertaking sizeable parts of the Staffordshire & Worcestershire in parallel. His foreman on the latter works, John Clegg, left two years later to become the first contractor on the Forth & Clyde Canal, and made quite a sophisticated arrangement with them about temporary works and commercial matters (Scottish RO: BR/FCN/1/2, 4Feb1769). Other companies preferred small contractors. The Birmingham Canal advertised for tenders from contractors, who were required to be quite free from prior engagements (RAIL 810/1, 30Mar1768).

Although competitive tendering was quite usual, it was also the practice to offer work at the rates which the Engineer had used in his estimate (RAIL 810/1, 8Apr1768). The Forth & Clyde also set its rates, and preferred small contractors, «in order to create emulation and give facility in the execution». Alternatively, a company could let its first contract when competition was fierce, and then offer the subsequent works to other gangs at the same rates (RAIL 816/2, 14May1773). In this case, the contractors were not to employ more than 40 men and their names do not appear in the records of other companies, suggesting that they were local men in a small way of business. Later, during the Canal Mania when clients were more in competition with each other, the Worcester & Birmingham offered a contract at a price which the contractor could not accept, and had to agree to their Engineer settling the difference (RAIL 886/4, 15Apr1793). The Ashby Canal was still offering work at fixed rates in 1797 (RAIL 803/2, 4Jan1797).

A third, less common method of agreeing a contract was for the tenderer to agree to accept prices to be fixed by the Engineer. This implied a degree of trust, which the contractor for the Shrewsbury Canal was willing to give to William Jessop or Thomas Dadford (RAIL 868/1, 6Jul1793), but proved very expensive to John Pinkerton on the Barnsley Canal (RAIL 806/3, 5Aug1793). This latter contract led to a protracted lawsuit when the Company failed to accept Jessop's recommendations for extra payments. In his judgement the Master of the Rolls recognised the changing nature of the role of the Engineer:

> Mr Jessop because he was the Engineer employed by this canal company supposed he was their servant also in fixing the prices at which this work was to be done & that he was to act in their behalf against . . . Mr Pinkerton. . . . but he unfortunately has fallen into a mistake with respect to the nature of the situation in which he was placed. (quoted in Hadfield & Skempton 1979, 137)

Financial strength

The changing financial strength of contractors can be seen in the terms of their contracts and the account books of the clients. On the Bridgewater Canal in 1759, John Beswick, mentioned above, was able to work without interim payment for six weeks, but the sum involved was only £38 (Northamptonshire RO: EB 1459). On the Staffordshire & Worcestershire in 1766 he was receiving sums of around £60 weekly (Staffordshire RO: Mr Baker's accounts).

These payments were in the nature of subsistence money, paid to the contractor at a daily wage for the number of men at work. The company would employ one or more Counters who would walk along the site in order to make a record. Interim measurements of work done, the proper contractual basis for payment, were often irregular and infrequent. The system frequently gave rise to substantial overpayments if the contractor had tendered too low. The impression given is that interim measurements were a low priority for the companies and their few, overstretched site staff, responsible also for progress and quality. But the companies could be quite harsh in these circumstances. The Kennet & Avon Canal ordered a prosecution of James Hollinsworth,

afterwards resident engineer on Waterloo and London Bridges, for £729 overpaid, and had him arrested. The matter must have been dropped at the time for they noted five years later that he was now in receipt of a considerable salary and might be worth pursuing (RAIL 842/3, 23Feb1805).

Between the 1760s and the 1790s a few contractors emerged who had saved enough from the profits of a succession of works to be able to undertake much more valuable contracts than anything which had been seen since the seventeenth entrepreneurs in the fen drainage. The Pinkerton family started in 1767, in partnership with an established engineer/contractor, with a contract worth about £5000 and soon were undertaking works of two or three times that sum. By 1775 they were able to undertake the whole of the cutting of the Selby Canal and in 1783 they tendered for the whole of the summit level of the Thames & Severn. (Gloucestershire RO: TS193/1). In 1788 they started on the Basingstoke Canal, for which their final payment amounted to more than £150,000. Their problems on the Dudley and Barnsley Canals have been noted above, though they earned a good reputation subsequently in the fens.

Two more consistently successful contractors were Hugh McIntosh and Sir Edward Banks (Chrimes 1995; Dickson 1931). McIntosh's career was the more conventional of the two. Starting with subcontracts, then moderate sized contracts for canals, he progressed to virtually the whole range of civil engineering work. Managing several contracts concurrently, and financing them to the amount of thousands of pounds between interim payments (ICE Rennie reports, 22.220), he amassed a fortune of some £300,000. Banks was two years younger than McIntosh but started independent work seven years later. He may have started work for the Pinkertons on drainage work in East Yorkshire, but his career flourished after he moved south and formed a partnership with the Rev. William Jolliffe. With other commercial interests outside civil engineering contracting, they too were able to finance large scale government contracts.

The Engineer on many of the contracts on which these men worked was John Rennie. When asked to give a reference for a proposed water supply, he described McIntosh as «one of the fittest persons I know for the execution of your works . . . He is besides a man of considerable property». Two years later he wrote to the West India Dock Company «I do not know any persons who will do the work better or more expeditiously than Messrs Jolliffe & Banks». But by 1820 he noted in a report to the Commissioners of the Navy that Banks was no longer giving close personal attention to the works at Sheerness [a contract eventually worth about £1.5 million in the money of the day] and the work was suffering as a result (ICE Rennie reports 11, 91).

McIntosh in particular seems to have developed the idea of the main contractor, describing himself in 1833 at Royal William Victualling Yard as the «contractor in possession of the main work». Whereas on earlier projects it had been usual to employ separate contractors for digging, masonry and carpentry, with the concomitant problems of coordinating their work, he objected to another contractor being employed to install the boilers for steam engines. On the Carlisle Canal in 1820 there is a clear reference to the need to have the Company's permission to sublet part of the works, and the main contractor's continuing responsibility for the due performance of the contract (Scottish RO: BR/CCC/1).

One problem for contractors is still with us today. It had been common practice on design-and-build contracts for bridges to require the provision of a financial bond from an independent guarantor against any defects arising during the maintenance period, which was often seven years. The sums could be unreasonably large, though common sense could prevail. John Cheshire, a well-known church steeple and bridge builder, was required to provide a bond of £1000 on a contract worth £2950 (Derbyshire RO: D533 A/TT17). He was unable to do so, but the bridge commissioners contracted with him nevertheless.

With the development of the designer/contractor split and supervision by full-time resident engineering staff, it became more usual to retain a percentage of the money due to the contractor, though the period was usually only one year. Again, the amount could be high. The Monmouthshire justices required £2000 retention on the £9500 contract for Caerleon Bridge (Gwent RO: D179.0001 and QS minute book 4, 246). Matters could be ameliorated by paying interest on the outstanding money, enabling the contractor to borrow the sum required, as was done at the Custom House Dock in Dublin. Some

engineers dispensed with the requirement. Francis Giles was one, and the contractor John Tredwell who worked for him thought 10% retention «a very serious difficulty against getting the work done cheap» (Parliamentary evidence, London & Southampton Railway 1834).

Most contracts contained a time or period for completion, but there were several examples of contractors being released from their contracts when it became apparent that they would be unable to complete on time. Sometimes this was done without penalty, as with Thomas and Benjamin Baylis on the Gloucester & Berkeley Canal, but John Pinkerton had to pay £2000 to leave the Dudley Tunnel, mentioned above. Clauses setting damages for lateness in completion were unusual but not rare. £5 per week was the rate for Blackfriars Bridge, Norwich in 1783, a contract worth £1250 (Norfolk RO: NCR 22a[4]).

The workforce

A suitable workforce was not always readily available. In 1768 the Birmingham Canal advertised in the Gloucester, York and Manchester papers for stonemasons (RAIL 810/1, 16Sep1768) and in 1776 the Stroudwater Canal in Gloucestershire recruited from Birmingham and Ripon, North Yorkshire (Gloucester RO: D1180/1). The Monmouthshire Canal advertised in Carmarthenshire and Cardiganshire (RAIL 500/5, 4Sep1792) and for miners the Grand Union in Leicestershire looked to Devon and Cornwall (RAIL 831/1, 11Jul1811).

Parliamentary evidence in 1834 suggested that many engineers preferred to employ local agricultural workers, Robert Stephenson being an exception, but this could give rise to problems at harvest time, when there was not enough labour either to take advantage of the summer to press on with the works or to gather in the harvest.

Much of the period to 1815 was one of wage inflation, and workmen could be enticed away. The Herefordshire and Gloucestershire and the Gloucester & Berkeley tried to suppress mutual poaching, though as the men were employed by the contractors it is not clear that they were successful. The Neath Canal passed a resolution that they would not employ anyone without a discharge from their previous employer, in the hope that other employers would reciprocate (West Glamorgan RO: D/D Nca85). The Grand Union Canal was more realistic, and paid loyalty bonuses to those of its workforce who did not go to the Fens, where work was seasonal but more highly paid (RAIL 831/1).

Accidents to the workforce were not infrequent, and employers gave grudging assistance to those who had been injured. In 1769 the Forth & Clyde Canal gave «such poor people who have been hurt at the works some small thing for their support during their recovery». By 1795 a more regular approach had become usual and the Peak Forest Canal introduced a sickness benefit fund, with rules and regulations, to which the workmen and the Company contributed. The following year Worcester & Birmingham gave the moderate sum of five guineas to the General Hospital «because of numerous accidents to the workmen». The Kennet & Avon Canal, having allowed £13 to one contractor, gave notice that in future they «would not allow any relief to the sick or lame . . . unless a fund by an allowance from the respective men's pay is established for that purpose as is usual on all other canals».

Conclusion

Much of the evidence in this paper has been drawn from the first part of the period from 1760, when work on canals formed the bulk of civil engineering construction. The major bridges, dockyards and ports constructed from 1800 were, with few exceptions, constructed under the supervision of engineers who had been involved in canal work. Developments in organisation continued, partly to satisfy the requirements of legislation, partly to deal with the increased size and complexity of the works but also as a result of experience. It can be seen that even by 1835 there was no unanimity about the ideal form of organisation, but there was enough knowledge of good practice to allow the extraordinary growth of the railway system in the years following.

Notes

1. References in the form «RAIL 8xx» here and subsequently are to manuscript items in the Public Record Office, Kew, London, UK. Page numbers in

minute books are sometimes missing or duplicated, so dates are given in references.

2. References in the form «county RO» here and subsequently are to documents in the Record Office of that county in the UK.
3. References in the form «ICE Rennie reports» are to manuscript volumes in the archives of the Institution of Civil Engineers, London, UK. There are twelve numbered volumes and one general volume by John Rennie senior. The numbers of the volumes by his son, Sir John Rennie, have had 13 added to them here in order to distinguish them from those of his father.

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The construction works in the first railway to the «meseta»: The Alar del Rey-Santander railway 1860–1866

María Luisa Ruiz Bedia
Rafael Ferrer Torio

Construction of railways in the 19th century

Spain constructed most of its rail network in the 19th century. One fundamental aspect of railways is their sensitivity to alignment both in plan and in elevation, and the broken nature of the Spanish terrain complicated the work of the engineering technicians. Many physical obstacles had to be overcome and many risks taken with works constructed in places of difficult access in order to create a continuous track formation and enable a steam-traction adhesion railway —which was suitable for flat or small-gradient railroads— to handle inclines such as those found in Pajares (Asturias), in Orduña (Vizcaya) and, in the case that concerns us, in Bárcena (Cantabria). Spanish civil engineers were responsible for project management and supervised the works, but they were aided by foreign experts brought in by the concessionary companies, as was the case with the railway we are concerned with.

The planning and building of a railway in 19th century Spain was no easy undertaking. Since there were no general maps, different line layouts could not be planned in advance. This meant that exhaustive fieldwork had to be done so that the most suitable route could be adopted. Once a route had been chosen, a tacheometric survey was undertaken of the area affected. This was reflected in plans on different scales and, after these had been made, potential routes were fitted, the track alignment was plotted, long sections were drawn, and finally, when the gradients had been established, the earth moving was calculated. When the track formation ran through favourable terrain, economic and regular alignments could be carried out based on long straight tracks joined by large radius curves, and minimum gradients. However, when it was necessary, as in our case, to link towns situated at very different altitudes and separated by mountains and narrow valleys, with only a few kilometres between them, work was made much more difficult, and the construction of the railway formation required the building of tunnels, bridges, viaducts, other minor engineering works, and also large retaining walls.

The Alar del Rey-Santander railway

The railway line between Alar del Rey and Santander was the first stretch of railway in the Cantabrian mountains. It was promoted by the common interests of landowners of Castile and businessmen in Santander, who wanted a suitable means of transporting wheat from the Canal of Castile (Alar) to the port of Santander. In 1845, the license was obtained and the civil engineer Juan Rafo was commissioned to study the route design, which was to have two fixed points, starting at Alar del Rey and ending at the port of Santander. His report, presented one year later, was discouraging: the state of knowledge at the time meant that certain limits for

gradients and curve radii could not be exceeded, and this and the difficulty of the terrain led to the project being divided into three sections. From Alar del Rey to Reinosa (first section) the obstacles were not too great because the two points were at a fairly similar altitude, and could be linked with maximum gradients of 16 pro mille; from Santander, access was made possible by following the gorge created by the river Besaya as far as Bárcena de Pie de Concha, and this constituted the third section. From here, however, a special study was necessary for the 15–km horizontal section from Bárcena to Reinosa and to overcome the 563–metre difference in height between them (second section). The preliminary studies analysed all the possible solutions, including the use of stretches with inclined planes; although these would solve the problem, they would make exploitation of the railway much more difficult.

In 1846, the project was studied by the *Dirección General de Caminos* (State Civil Engineering Department) according to the recommendations outlined in the Subercase Report. This report, made by the engineers Santa Cruz and Subercase, indicated that the use of inclined planes in the gorge of Hoz de Bárcena contravened the technical recommendations in railway legislation, and they advocated reducing the gradient by lengthening the route. Nevertheless, the line layout proposed by Rafo was finally accepted and authorisation was given to use gradients exceeding the established limits. However, the enormous financial outlay entailed in carrying out the work discouraged the concessionary company and the project was forgotten until 1851, when the granting of a new license (to the *Compañía del Ferrocarril de Isabel II*; Isabel II Railway Company) and a governmental reorganisation (new *Ministerio de Fomento*; Ministry of Public Works) finally led to the construction of this railway link. The section between Alar del Rey and Reinosa came into operation in 1857, Santander-Bárcena in 1860, and the most complicated section six years later. During this period, locomotives had been improved and were now capable of dealing with steeper gradients; this meant that the original project could be modified and a new alignment planned that did away with the inclined planes. The work was completed in 1866, almost ten years after the first section had come into operation. The delay greatly hampered the transport of goods, which could be moved quickly to Alar and to Reinosa, but then had to be unloaded, stored, and transported by horse-drawn wagons to rejoin the railway before finally reaching the port of Santander.

Solutions for the Reinosa-Bárcena section

The difficulties presented by this section were enormous. The difference in altitude between Reinosa and Bárcena was 563 metres: 242 metres between Reinosa and Pesquera, which were 14 km apart, and 321 metres between Pesquera and Bárcena, which were separated by 7 km. The first solution consisted in covering the distance and difference in height by following the right side of the river Besaya and using four inclined planes: the first in Aldueso and the other three in the gorge of Hoz de Bárcena (from Ventorrillo to Bárcena de Pie de Concha). The total distance was over 8 km, with gradients of up to 10 % required to overcome a vertical elevation of 452 metres. The route design was planned to go through the gorge with straight alignments for each stretch and a winding engine at the head of each inclined

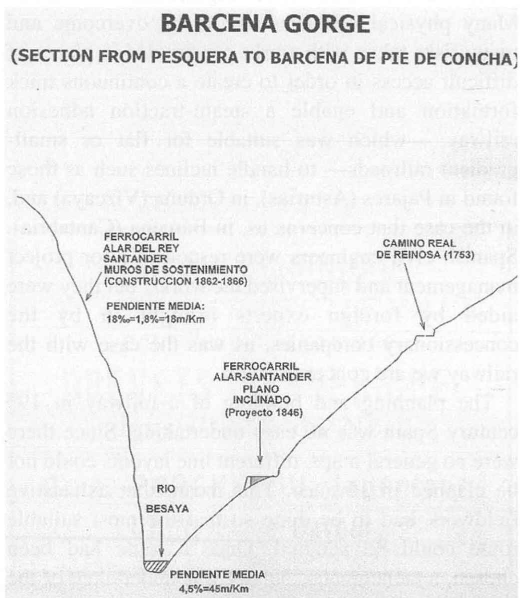

Figure 1
Corridor used for the railway line

plane to raise and lower the railway trucks. This operation would have hampered use of the line and would have made it far more costly to run. One of these inclined planes would probably have had a straight alignment coinciding with the present main road (N-611), which lies below the original *Camino Real de Reinosa* (royal highway), as can be seen in figure 1.

A later study made it possible to eliminate the inclined planes by forcing gradients to the limit (stretches of 22 pro mille) and by making the route much longer. Figure 2 contrasts the two design criteria. The short route, of some 18 km between Reinosa (height above sea level, 848 metres) and Bárcena (285 metres), made use of inclined planes. Without these, the length of the route was 34 km, an increase of 16 km. This was the solution adopted and it meant using a more circuitous route and many expensive engineering works (tunnels and cuttings), breast walls and retaining walls. Figure 3 shows the line layout required to eliminate the inclined planes.

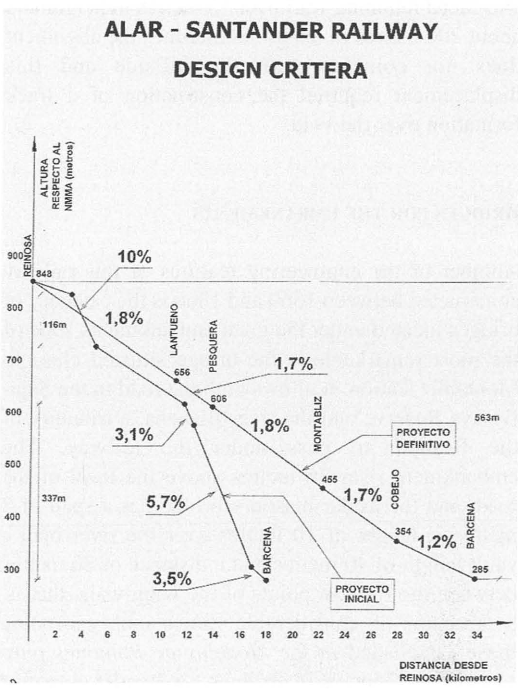

Figure 2
Long section comparing two design criteria

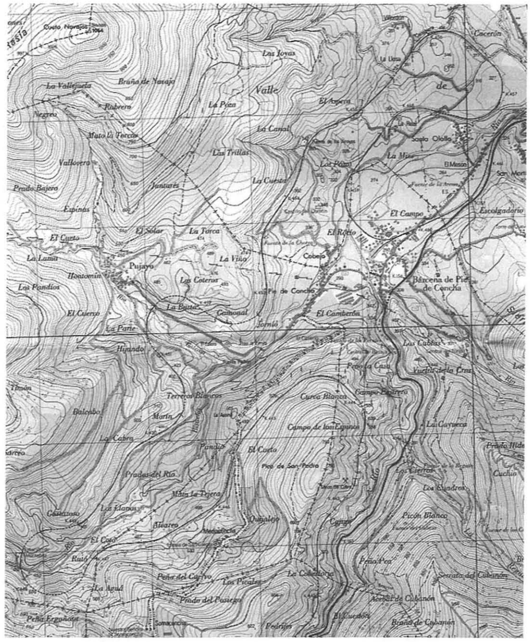

Figure 3
National Topographic Map (MTN-25). Development of the track alignment to avoid inclined planes

This decision involved situating the railway to the left of the river Besaya and making a descent that hugged the hillside. This is shown in Figure 4. The left side of the river Besaya consists of sandstone and the railway line makes its way down the valley by means of tunnels, large cuttings and the construction of breast and retaining walls for which the stone obtained in excavation was used in both ashlar masonry and coarse masonry.

Retaining walls

The stretch of railway between Pesquera (altitude, 606 metres) and Montabliz (altitude, 455 metres), a crossing point on the single line railway now obsolete, includes the most important retaining walls in the Reinosa-Bárcena section. Figure 5 gives an aerial view of the narrow gorge as it descends towards the coast. The river Besaya is flanked on its right by

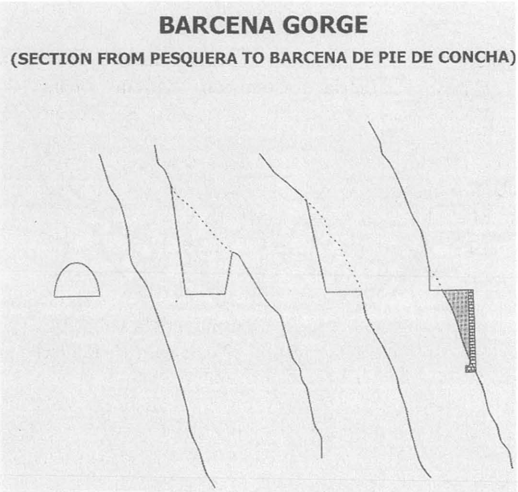

Figure 4
Types of solutions with engineering works

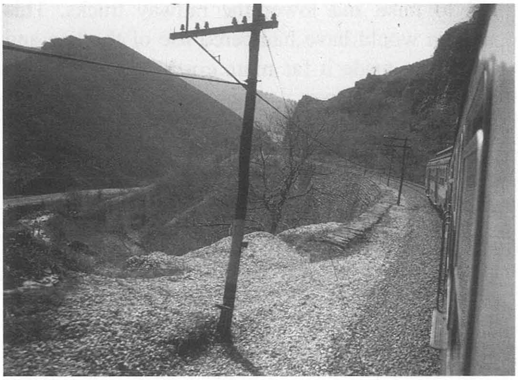

Figure 6
Hillside retaining wall

the present-day main trunk road (N-611) and above this is the old royal highway (*Camino Real de Reinosa*). To the left of the river is the unmistakable geometry of the railway track; in many parts, the track formation required the construction of engineering works based on rough masonry, ashlar masonry and rough ashlar work, which are outstanding for their meticulous execution.

These walls constitute track formations up to 10 metres long and 30 metres high, and they alternate

Figure 5
The line layout and its field of influence

with tunnels throughout the descent. Figure 6 was taken from a moving train and shows the finish of one of these hillside walls where what is striking is the correctness of the ashlar coping. In other parts, it was necessary to create a complete track formation with a two-faced retaining wall over 15 metres in height and about 200 metres in length. Sometimes the alignment does not coincide with the hillside and this displacement required the construction of a track formation over the void.

Bridges for the embankments

Another of the engineering features of this railway constructed between 1860 and 1866 is the category of bridges located under the great embankments. One of the most remarkable is the bridge situated close to Montabliz station. It allows both the road to the Saja-Besaya Reserve and the river Bisueña, a tributary of the Besaya, to pass under the railway. The embankment rises 16 metres above the level of the road, and the ashlar masonry bridge has a span of 8 metres, a height of 10 metres over the river bed, a vault length of 40 metres and a distance of 80 metres between the furthest points of the wing walls-that is, a structure of considerable dimensions exceeding those established in the *Modelos de Pontones para Carreteras* (Models of Bridges for Roads) compiled by the Commission of Civil Engineers in 1858, in which the maximum values recorded were spans of 6

metres and heights of 10 metres. In both cases, the typology was very similar with semicircular arches, ashlar and coarse masonry, and elements such as abutments, wing walls, barrel vaults and dressed coping stones.

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Construction techniques and auxiliary facilities used in the construction of masonry and early concrete dams

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Ana B. Barco Herrera

The evolution in the design and construction of dams —since the first dam building we know of— has been largely conditioned by three basic factors: Knowledge and use of materials, technological development and the scientific knowledge of each period. These three aspects are closely related, and it is very difficult to establish the precise role played by each of them through the course of history. However, it is possible to identify those periods in which the most significant progress was made in each of these fields.

As far as knowledge and use of materials is concerned, it was the Roman engineers and architects who improved and generalised the use of lime mortars, and began the addition of puzzolanic matters. The second relevant period in the use of materials was not to come until the end of the XVIII century, when J. Smeaton begins the first investigations which were to lead to L. Vicat manufacturing an artificial cement in the first quarter of the XIX century. The early decades of the XX century constitute what is known as the initial concrete phase, in which concrete for large blocks reached its maturity and gradually replaced masonry (Díez-Cascón and Bueno 2001). The second phase, which continued up until the 70s, saw the maximum state of development of conventional concretes. The final phase in the evolution of the concrete used for dam construction begins in the progressive development of rolled compacted concrete.

The technology of manufacture and building developed by the Romans builders, understood as the optimisation of resources, rational organisation of work and the «normalization» of procedures, was not improved until the end of the XIX century when the use of steam power spread to the machinery used in dam construction.

Scientific knowledge of the behaviour of dams includes the study of the laws which define both the behaviour of structures and their foundations, as well as the hydraulic performance of the outlets; disciplines which, because of their interrelation and dependence in the case of dams, must necessarily be studied together.

The first qualitative leap forward in the study of structural behaviour occurs in the second half of the XIX century, when Sazilly, Delocre and Rankine propose the first rigorous calculation methods based on the principles of rational mechanics.[1] The first decades of the XIX century were to see great advances in this field, with the appearance of the first modern methods for the structural analysis of different types of dams.

The hydraulic knowledge employed in the construction of the first dams is intuitive in nature and only partial. Research into this area begins in Italy during the XVI and XVII centuries,[2] and makes important progress in France during the XVIII century.[3] The XVIII century sees the emergence of great French and English engineers,[4] who direct their efforts at the theoretical study of fluid kinematics. The last great leap forward in the field of hydraulics

occurs at the beginning of the XX century when, through dimensional analysis and systematic experimentation, it focuses its attention on the study of local effects.

Studies relative to foundations are more recent. On the one hand Soil Mechanics begins in 1773 with the contributions of Coulomb, developing through the XIX century up until the boost given by Terzhagi in the first quarter of the XX century; while Rock Mechanics, emerging in Switzerland at the end of the XIX century, does not reach maturity until the mid XX century.

Hence, the first time in history when the advances in the fields of materials, technology and scientific knowledge in relation to dam construction really coincide is that which covers the period from the mid XIX century to the first decades of the XX century. This period of great advances implies for masonry dams the transition from masonry to concrete, along with a profound transformation of the auxiliary facilities and construction techniques. This paper centres on the relationship existing between the change in the material used and the evolution of facilities and construction techniques employed during this period.

The evolution of facilities and construction methods in masonry dams

Focusing solely on the advance in knowledge of materials and technology available, we can establish the following periods in the evolution of masonry dam design:

- Pre-technological period, up until 1850.
- Maximum development of stone masonry dams.
- The first concrete dams.
- The development of conventional concrete dams.
- The development of rolled compacted concrete, since the last quarter of the XX century.

Excepting the first and last stages, both the extension and the beginning, as well as the end of each of these periods varied between countries. In this paper we make a comparative analysis of the development of dams in the United States —which we use as the country for reference during the period studied —and in Europe.

Pre-technological period

This period, which covers from the construction of the first dams —the first references go back to the third millennium BC— to the mid XIX century, is characterised by the slow evolution in their design and construction (Schnitter 1994). The references available about auxiliary facilities and construction methods are scarce, and these can only really be studied by looking at the remains of dams still visible today and from the references available about other engineering work such as bridges, roads, etc.

It seems clear that in each period the construction techniques used were similar in all these types of construction, adapted to the volume and importance of each. Thus, animals were used for transport, while on the work site itself the positioning of materials was done manually, with the aid of pulleys, burtons and other similar devices for lifting when the weight was too great (Díez-Cascón and Bueno 2001). Figure No 1 shows a representation by a modern artist of a type of crane[5] —following a description written by Vitubrio— used by Roman engineers in their constructions to lift large blocks of stone. The facilities used to shift materials cannot explain the qualitative leap represented by Roman constructions, which could only be performed thanks to the rational organisation of building work and the development or improvement of other auxiliary facilities such as topographic and dewatering instruments.

The posterior improvement of Roman construction techniques and auxiliary facilities was very slow and it would probably be more precise to refer to the next centuries as a period of progressive perfection rather

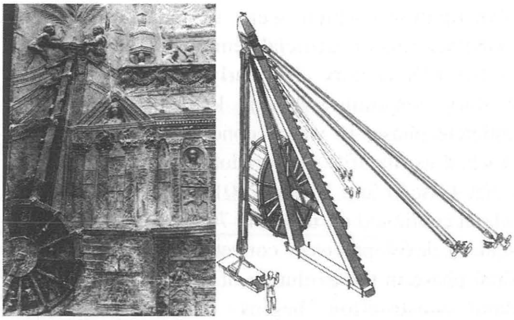

Figure 1
Roman Crane

than of evolution. As an illustrative example, figure No 2 shows the designs made by J. Betesolo and J. de Laguna for the cranes used in the construction of El Escorial, which differ from the Roman cranes only in the steel truss on which they stand, thus becoming a forerunner of present day cranes (García 1997).

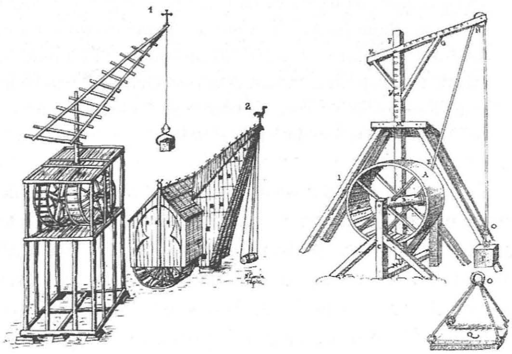

Figure 2
Crane designed for the construction of El Escorial. (Spain)

Analysis of the most representative dams of this period[6] allows us to affirm that they were not constructed thanks to any significant innovation or improvement in auxiliary facilities, which were still to be a long time coming.

Maximum development of stone dams

The auxiliary facilities and mechanical devices using animal power, workers or hydraulic power reached their peak development during the first half of the XIX century. The fact that the majority of dams were built far from population centres, combined with the scarce economic resources available for their construction were just some of the causes for the delay in application of steam power for construction with respect to other types of building work and industrial activities.

In the mid XIX century in Europe and the United States steam power begins to be used in dam construction for the operation of cranes, workshop and quarrying machinery, transport of materials and generation of electrical energy. Although this application is initially rudimentary and its use is very patchy —even within a single country— depending on the characteristics of each work, this fact and the start of the use of artificial cement mark the beginning of the fastest and most important advance up until then in dam construction. Thanks to the continuous technological improvement of auxiliary facilities and the quality of cements, the last quarter of this century and the first three decades of the of the XX century constitute the «golden age» of stone masonry dam construction, both with regard to the number of dams and the dimensions of the projects.

One of the direct indicators of the degree of technological development of the auxiliary facilities used in dam construction is the relationship between volume of the dam built and the manpower employed. The progressive increase in the cost of this manpower accelerated the development of better auxiliary facilities. The construction of the Pontón de la Oliva Dam[7] is a representative example of the massive use of manpower during the mid XIX century.

Despite being the most important hydraulic work in Spain at the time, the auxiliary facilities used were very limited. Up to four hundred animals, one thousand five hundred prisoners and two hundred workers were employed for excavation of the foundations; five hundred of them to manually pump out the foundation ditches, aided by four steam pumps (Bello 1929). The increase in manpower costs and the development of specific machinery for excavation and transport would make it possible, barely half a century later, to excavate the foundations of the great American irrigation dams, such as for example Eléphant Butte Dam,[8] using totally mechanised means.

Obtaining materials and transport to the site

In the mid XIX century, the location of the first masonry dams was almost totally conditioned by the existence of nearby stone quarries from which to obtain the necessary stone, both in the volume and the size required for stones and ashlars. The low density of land transport networks made it necessary to use beasts of burden –along roads and paths especially opened up for the purpose —in order to transport materials and the limited auxiliary facilities. Equally, the absence in the proximity of the dam of limestone

quarries to manufacture hydraulic lime made it necessary to transport it from the scarce factories existing. This meant a considerable increase in the cost of the work despite the poor dosage of the mortars and the reduced percentage per cubic metre of masonry.

The continuous improvement in quality of the artificial portland cements meant that the hydraulic limes and natural cements[9] fell into decline. The increase seen in the last decades of the XIX century in the dimensions of dams, and the richer dosage of mortars in stonework, means that the volume of cement rises considerably. These improvements in the materials used were not accompanied by significant improvements of transport facilities available, which on many occasions meant that it was necessary to set up artificial cement mills at the dam site. For the construction of the Rooselvelt Dam,[10] the lowest bid received from cement manufacturers for cement delivered at the dam site was $4.89 per barrel. The Reclamation Service found cement materials at the dam site and there built and operated a cement mill with a capacity of about 400 barrels per twenty-four hours. The mill operated for a period of about five years and three months with a total output of 338,452 barrels, the average cost being of $3.14 per barrel.

The reduction in manufacturing and transport costs, thanks to the technological development of the railways and other auxiliary means of transport, gradually generalised the external supply of cement for the manufacture of mortars and concretes. An illustrative example of the difficulties caused by the location of dams in largely inaccessible places, and the growing complexity of the auxiliary facilities used for the transport of the cement and of the equipment used for its construction, is the case of the Gem Lake Dam:[11]

> . . . where the cement had to be transported 500 km by wide gauge railway, 135 by narrow gauge, 110 along desert terrain, with caterpillar tractors, thus being brought to the machine house. It was then loaded onto a tram, covering 1500 m with a 375 m difference in altitude; it was then transported on barges across Gem Lake and was loaded onto another tram, upon which it climbed another 165 metres (Gómez-Navarro, 2: 989).

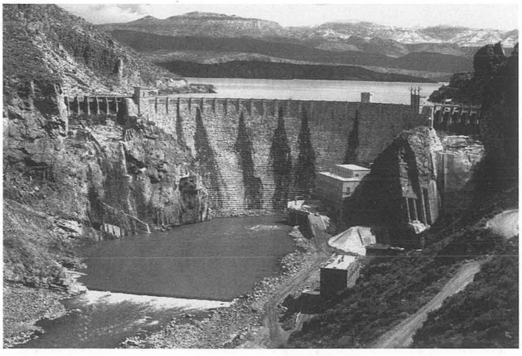

Figure 3
View of Roosevelt Dam. (USA)

The facilities and construction machinery available at the beginning of the XX century made it possible to easily construct long tracks —even in high mountains— for access to the dam site. In some cases in which the terrain was not too abrupt and the volume of material to be transported was important, sections of railway line were made especially; this system was limited —until well into the XX century— to the most industrialised countries such as Great Britain.

Possibly the «The Elan Valley Dams» constitute the group of dams which best define the state of technology at the turn of the century. These dams, constructed in the high moorlands of mid-Wales, would permit the water supply to the city of Birmingham by a huge pipeline over 70 miles long. The scheme, developed during the last decade of the XIX century and the first decade of the XX century, consists of six masonry gravity dams with well finished ashlar facing.[12] Although these dams do not stand out individually for their height, dam volume or water capacity, the most advanced auxiliary facilities of the time were used in their construction. Their joint planning, together with the organisation and optimisation of the auxiliary facilities, was to mark the pattern for masonry dams during the next four decades.

Before work could start on the construction of these dams, however, it was first necessary to build an extensive private railway network. This was required to transport the massive amounts of building materials and essential supplies needed at many sites, widely spread within the two river valleys. At the peak of the dam-building operation the network is thought to have extended to some 33 miles in length,

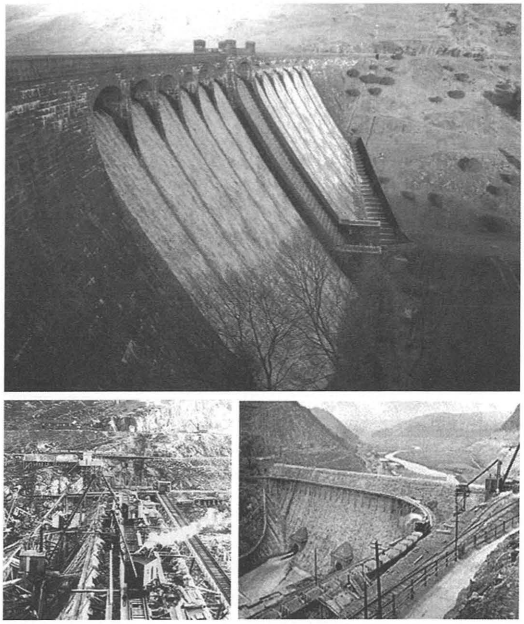

Figure 4
Construction of Elan Valley dams. (UK)

and eight saddletank locomotives were used to move about one thousand tons of building materials every day. Many of the branches of the Elan Valley Railway network ran along the bottom of the valleys, which were flooded after the completion of the dams. These linked quarries, cement sheds, workshops, and stone-dressing yards with the construction sites at the base of the dams. Temporary branch lines were also used at various levels, cut into the sides of the valleys for delivering stone and other materials as close as possible to where they were needed. So the layout was always changing as the work went on. A common practice for all the dams was to use a section of railway track cantilevered out from the face of the towering dam wall. These were supported by timbers resting on masonry pegs jutting out at regular intervals along the almost vertical dam wall. In spite of the danger, this arrangement was very successful.

Despite this progress, the transport of materials and of the auxiliary installations to abrupt terrain, devoid of any access routes, meant that more specific systems had to be developed. The construction of the Camarasa Dam[13] made it necessary to build a funicular railway 415 metres long and up a 22% slope to transport materials up to the cement plant located at the top of the slope. For the construction of the dam at Chambon in France a decade later, the scheme would be repeated using the most modern means and materials of the moment. The monocable funicular was 10450 m long, supported on 62 metallic towers up to 40 m in height. The maximum span between towers was 868 m and the height difference 535 m. The 193 dump cars, with a capacity of 250 Kg, were spaced at 120 m and moved at a speed of 2 m/s, which assured the transport of 15 Tn/hour (Gómez 1932).

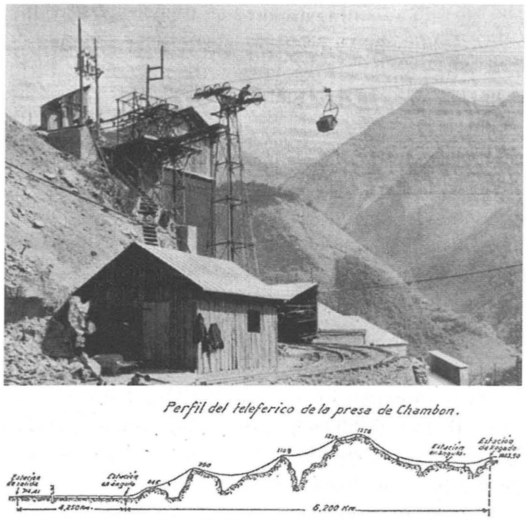

Figure 5
Monocable funicular. Chambon Dam. (France)

Transport of materials to the body of the dam

The correct organisation of the transport of the materials manufactured from the quarries, workshops and mixers to the dam site and their transport to the final worksite is more complex and more decisive from the point of view of the rhythm of construction than the transport of materials and facilities from the supply areas to the construction zone. It is probably in this phase where one can best appreciate the differences in technological development between countries.

The description of the facilities and methods used in the construction of the El Villar Dam —a spanish masonry dam 56 m. high and built between 1870 to 1879— is a significant example of the scarce introduction of mechanical power in the construction of spanish dams during the second half of the XIX century, despite the fact that the number of dams built and their dimensions was of great importance. The transport of materials to the site of the aforementioned dam was done by horses which descended the steep paths opened for the purpose, while the dewatering of the foundations was done using two Letestu double body pumps. The transport of stones and ashlars from the quarry, situated above the top of the dam, to the site was done using a system employed, with continuous improvements, in numerous Spanish dams and in the rest of the world. The ashlars were transported in wagons to the edge of the slope and they descended the slope on an inclined surface with two parallel tracks along which the ascending and the descending wagons circulated, the two being joined by a strong chain which went through a pulley situated at the top (Boix 1875). This same scheme, substituting manpower with electrical power or with power from internal combustion engine, would be repeated for various purposes in the construction of the Infante Jaime Dam and Príncipe Alfonso Dam, work on which was terminated in 1923 and 1930 respectively. Once the wagons which transported the heaviest stones reached the head of the dam, their distribution was done by a complex network of auxiliary rails to the cranes. This arrangement, which on occasions greatly complicated the work, was gradually simplified when the cranes used increased in capacity and other auxiliary facilities such as cableways appeared.

The construction methods used in other more technologically advanced European countries, followed similar schemes, but the results were far superior due to the use of much more specialised machinery and the massive use of steam power. In the construction of the Virny Dam,[14] barely ten years after the Spanish El Villar Dam, seven steam cranes were employed, each with an engineer, and eighteen men laid an average of 40 cubic yards per day. Another representative example are the dams of the Ellan River Valley, mentioned earlier, in which the transport to the dam itself was done using auxiliary rails, branching off from the main lines of communication between the different dams, and along which big wagons were pushed by locomotives.

Figure 6
Construction of Camporredondo Dam. Inclined surface for the transport of materials to the damsite. (Spain)

In the construction of masonry and concrete dams during this period, the type of crane used in most cases is that known as a «derrick». This name, of American origin, has been applied by analogy to different cranes with similar mechanical systems and powered by different types of energy. The initial American scheme of the derrick crane was a long oblique arm, articulated at its base, and tightened at the top end to a tripod anchored to the ground, which permitted the base to turn and the load to be moved vertically. Both the tripod part of the crane, which was held in place by great blocks of stone, and the sloping mast were originally made of wood for ease of dismantling and of transport to other sites.

The evolution in the design of derricks —as to load capacity, mast scope and energy source— was very rapid as from the last two decades of the XIX century. However, this process was not equal in all countries; there was a clear difference between those countries which habitually used the most advanced cranes — the USA and Britain— and the rest, in which their use was limited to the most important dams. The factors which influenced this use were numerous and included the dimensions of the dam, the availability of other facilities to move the derrick from one site to another, the use in the construction of steam or electrical power, the maximum weight to be shifted and the characteristics of the site. This is the reason of

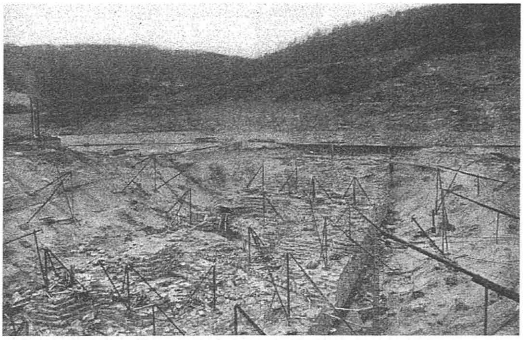

Figure 7
Construction of New Croton Dam. Arrangement of derricks. (USA)

the co-existence in a single country —and even at times on a single worksite— of technologically very different cranes.

Thus, the use of derricks operated by steam power was already common in England in 1885, and by the beginning of the XX century a degree of development in the use of cranes and other auxiliary facilities had been reached which was not surpassed in the first three decades of the century. The following quotation, in reference to the construction of the Ellan valley dams at the beginning of the XX century, reflects the degree of development of auxiliary facilities and their correct organisation on the worksite:

> It may be observed here, in illustration of the skilful organisation of these large works, where over 1,000 men are employed, that in the whole of the operations only seven horses are in use, though one or two more will be required later on as the work increases (Barclay 1898).

At the beginning of the XX century, the progressive increase in the number of derricks used in dam construction made it essential to study, prior to commencement of the work, the most suitable location for each of the cranes during the various phases of construction. Depending on the dimensions of the dam and the means used to move the derricks, these would be positioned outside the faces of the dams, aligned longitudinally beneath the cableways, mounted on rails or steel trusses which were imbedded in the interior of the body of the dam (Smith 1915).

No only did this increasingly intense use of auxiliary facilities increase the rate of construction, but it also modified the mentality of dam construction».In a few years the consideration of the facilities and installations as individual elements changed and they began to be seen as a planned group in which each fulfilled a function, did not hinder the rest and collaborated in the final result, appearing what could be called «The planning of Dam Construction». (Díez-Cascón and Bueno 2001)

La Peña Dam[15] is the first Spanish dam in which the perfect location of all the auxiliary facilities, the clarity in the realisation of the work and its general cleanliness stand out. The construction in Spain of the first great hydroelectric systems will accelerate this process since, unlike irrigation and flood defence work done by the State, private companies needed to make greater investment in auxiliary facilities and in the organisation of the work itself in order to reap benefits on capital in as short a time as possible.

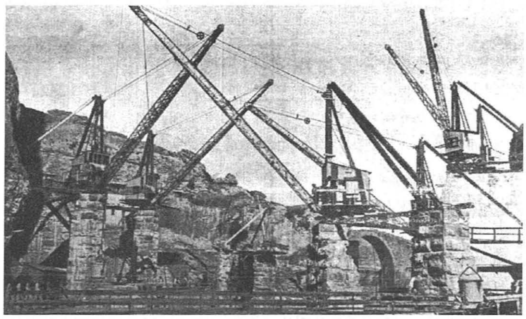

Figure 8
Construction of La Peña Dam. (Spain)

Power sources

Although the use of steam in the machinery used for dam construction is late compared with other industries activities, its use continues until the second decade of the XX century. British constructors were the first to systematically and intensively use steam, employing it to move small locomotives, cranes, and various workshop and quarry machines.

Early on, equipment powered by compressed air was found to be very valuable in the course of the

construction work. The air compressors were then known as «wind-jammers», and they made use of very long tubes to power tools at some distance from the steam-driven power source. This type of plant was used for drilling rock to make holes for dynamite, for drilling in quarries, and for use in metal working shops. An account written in 1898, referring to the construction of the Elan Valley dams, noted that: «so widely distributed is the plant that there are something like two miles of tube employed from the one station».

Technical and technological progress boosted by the First World War meant that from 1920 it was possible to introduce the internal combustion engine and caterpillars in moving machinery, while all engines were soon replaced by electric ones. From the third decade of the century diesel engines replaced electric ones in certain types of work.

Electrical power for operating machinery was initially obtained from small steam generators[16] and the construction of small hydroelectric jumps close to the worksite.[17] Later, the development of the large electricity networks meant it was easy to link up to them by means of auxiliary lines, which in some cases were extremely long.[18]

THE FIRST CONCRETE DAMS

The introduction of artificial cement in dam construction begins in the mid XIX century. Initially it was used individually or mixed with hydraulic lime, the first mortars being characterised by a very poor dosage of conglomerate. The need to increase the solidity of dams —increasingly large in size— and the fall in the price of cement due to increased production explains why at the end of the century masonry dams are constructed with cement mortars, and the dosages are more and more generous. At the turn of the century the first concrete dams appear,[19] thus beginning a process of transition which is to extend to the fourth decade of the century. From this moment, the construction of masonry dams will be limited to sites with special local conditions.[20] This process of evolution is led by the American constructors mainly because of the greater development of the American cement industry —which was able to adapt rapidly to new needs— and in part because of the lack of labour in rural areas.

This change in the material used is possible thanks to better knowledge of materials, but is also largely conditioned by the development of specific auxiliary facilities for getting the concrete to the worksite, without which the change would not have come about or would have taken much longer. This fact also explains the leadership of the Americans, since the greater European tradition for construction of masonry dams acts as a hindrance, by trying to apply the traditional methods used for positioning masonry on site to concrete.

The installations for the manufacture of materials were reduced in the case of masonry dams to the equipment needed for working the quarry, a storage area for the conglomerate and a manual or animal-powered mixer. The introduction of steam power permitted the later use of crushers to obtain artificial sand, sand washing equipment and automatic mixers with greater capacity.

This scheme is greatly complicated with the introduction of concrete, which makes it necessary to develope new and more powerful auxiliary facilities, which in turn require greater precision and reliability as they become the key to productivity in construction. Amongst this equipment the following are noteworthy:

- Crusher plant and facilities for washing and classification of dry materials.
- Silos for cement and dry materials.
- Sand, stone and cement mixers.
- Laboratory for control of materials.

The auxiliary facilities for the placing of the material on the dam used up until this moment are not suitable for this new material, and their adaptation for the simultaneous transport of concrete and a certain amount of large stones does not achieve the desired rate. This situation makes it necessary to develop new construction methods, to use new auxiliary facilities and to improve the existing ones.

The use of cableways to transfer the materials to the dam developed quickly in the first years of the 20th century; either for American masonry dams, as Pathfinder Dam and Roosevelt Dam, or cyclopean concrete ones. This system was first applied in Spain during the construction of La Peña dam. Cableways were the most economical machines possible in a large number or variety of cases. Besides handling the material with celerity and a minimum consumption of power they were available for many

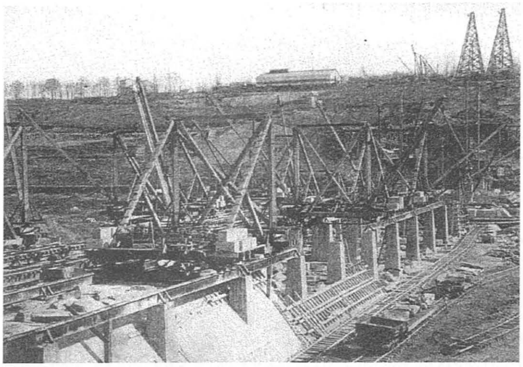

Figure 9. Construction of Kensico Dam. Arrangement of derricks and cableway towers. (USA)

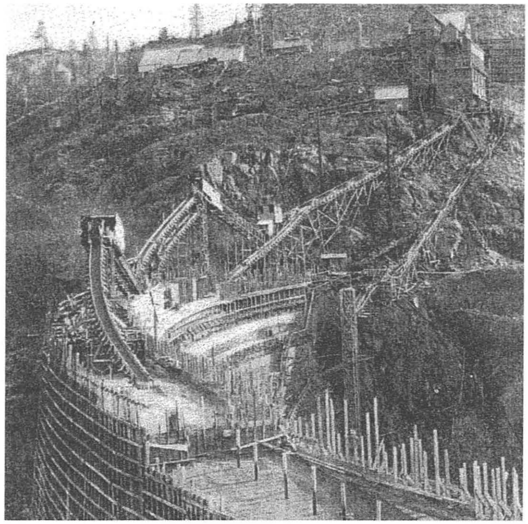

Figure 10
Construction of Spaulding Dam. Belt conveyor for concrete. (USA)

incidental operations such as erecting, moving, loading or unloading heavy items of equipment or material.

The first configurations of the cableway systems were very variable. They consisted of two or more parallel cables with fixed anchorages to towers placed in both ends of the dam. When the topography at the end of the dam permitted, they might be arranged so as to traverse up and downstream, for which purpose the towers and anchorages were mounted on trucks running on several tracks. This configuration was useful to reduce the number of cables needed. The load was transferred to the dam with the help of a hook —able to move vertically— connected to a carriage that travelled along the cables.

Another way of placing the material on the dam was the use of trucks running on tracks to the derricks that transferred the trucks to the place of use. This

Cableways used in the construction of some Spanish and American dams

Presa	Fecha	Height	Country	Length	No cables	Load
Sodom	1888–93	29 m	United States	203 m	2	6 ton
Pathfinder	1905–09	65 m	United States	107 m	2	15 + 10 ton
Cross River Dam	1905–07	52 m	United States	381 m	2	
Olive Bridge	1908–13	76 m	United States	468 m	4	
Owyhee	1928–32	127 m	United States	398 m	1	25.4 ton
Boulder	1930–36	221 m	United States	784 m	6	5 × 25.4 + 150 ton
Norris	1936	80 m	United States	586 m	2	18.3 ton
Talarn	1912–16	86 m	Spain	320 m	2	11 ton
Ricobayo	1929–34	95 m	Spain	310 m	4	11.5 ton
Cuerda del Pozo	1931–41	40 m	Spain	505 m	2	4 ton

method, similar to that used for masonry was only suited to very long, but not very high dams.

The way of delivering the concrete by chutes and belt conveyors was developed in the USA in the second decade. The concrete was elevated at some centrally-located tower, dumped into a hopper and then distributed by means of chutes, which were suspended from guys or from an arm or boom revolving in a horizontal plane about the tower as a centre. This method was used for the construction of the Lake Sapulding Dam, 1912, reaching a rate of 200 cubic yards per hour.

A system similar to the previous one consisted of the use of towers and chutes into which the concrete was poured with a quantity of water. This system was first used during the construction of Talarn, Camarasa and Montejaque Dams in Spain, Barbarine and Spitallamen Dams in Switzerland and Baker and O'Shaugneysen Dams in the USA.

Finally, in very long dams, a bridge or an auxiliary structure was built parallel to the dam and along which the materials travelled and from which they were poured onto or were transported to the body of the dam. During the construction of the Big Creek main dam, a construction trestle the full height and length of the dam was built in twenty six days just outside the upstream face, and coinciding with the line of the face so that the trestle timbers also served to support the forms. From cars running along the top of the trestle concrete materials were delivered to the twelve mixers installed within the trestle below; from the mixers wooden chutes conveyed the concrete to the dam.

With the use of concrete in the massive body of the dam, the importance of heat dissipation during setting increased considerably, becoming a major factor to be taken into account during construction. From this moment on it becomes necessary to use contraction joints, such that dams are no longer built as a solid block shuttered between two parameters of masonry, but rather as multiple blocks shuttered using wooden or metallic sheets. The need to alter shutters between the blocks and the fact of breaking the continuity between the different worksites makes it necessary to increase the number of auxiliary facilities and their aerial transport to the different parts of the dam.

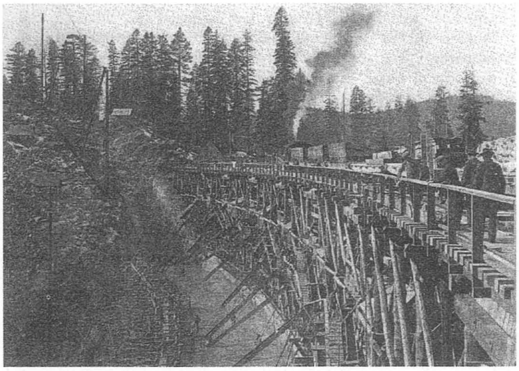

Figure 11
Construction of Big Creek Dam. Delivery of materials to mixers and delivery of concrete from mixers. (USA)

Conclusion

The analysis carried out of masonry and concrete dam constructions during the period from the mid XIX century to the first decades of the XX century shows the profound changes which took place both in the materials used and in the facilities and methods employed.

The relation between the change in material and the technological progress reached by the auxiliary facilities is two-directional. On the one hand the improvement and development of new auxiliary facilities would have been much less marked, since once the organisation and performance achieved in masonry dams reached its peak it would have made no sense to use more complex technologies. But at the same time, if the technological advances of the XIX and XX centuries had not taken place, then the use of artificial cement would have been reduced for many years to the manufacture of better quality mortars for masonry, and so the use of concrete in dam construction would have been delayed considerably.

Notes

1. The first applications of Rational Mechanic to the analysis and construction of dams were made in France in the period that covers from the mid XVIII to the mid

Performance of masonry and concrete:

Average rate of construction in some Spanish and American dams

Presa	Fecha	Height	Country	Type	Rate
Guadalcacín	1906–10	44 m	Spain	Rubble masonry	31 m^3/day
La Peña	1910–13	59 m	Spain	Rubble masonry	100 m^3/day
Buseo	1914	51 m	Spain	Rubble masonry	60 m^3/day
Talarn	1912–16	86 m	Spain	Cyclopean concrete	300 m^3/day
Infante Jaime	1916–23	37 m	Spain	Rubble masonry	50 m^3/day
Príncipe Alfonso	1922–30	76 m	Spain	Cyclopean concrete	150 m^3/day
Camarasa	1919–20	92 m	Spain	Concrete	650 m^3/day
Gallipuen	1927	38 m	Spain	Concrete	35 m^3/day
Jándula	1928–32	90 m	Spain	Concrete	600 m^3/day
Fuensanta	1933	83 m	Spain	Concrete	300 m^3/day
Ricobayo	1929–34	95 m	Spain	Concrete	800 m^3/day
Sodom	1888–93	29 m	United States	Rubble masonry	2295 m^3/month
Titicus	1890–95	33 m	United States	Rubble masonry	2480 m^3/month
New Croton	1892–1906	72 m	United States	Rubble masonry	13150 m^3/month (max)
Boonton	1900–06	31 m	United States	Cyclopean masonry	16065 m^3/month (max)
Pathfinder	1905–09	65 m	United States	Cyclopean masonry	3856 m^3/month (max)
Cross River Dam	1905–07	52 m	United States	Cyclopean masonry	14100 m^3/month (max)
Croton Falls	1906–11	53 m	United States	Cyclopean masonry	18525 m^3/month (max)
Arrowrock	1911–15	107 m	United States	Concrete	43 m^3/man/month
Owyhee	1928–32	127 m	United States	Concrete	140 m^3/man/month

XIX century, using profiles which can be qualified as «exiguous» and «mistaken» (Díez-Cascón and Bueno 2001).

2. Leonardo da Vici, Galileo, Catelli and Torricelli.
3. Bernouilli, Euler, Lagrange, Poleni and Bossut.
4. The French: Chezy, Navier, Cauchy, Saint-Venant, Darcy, Bazin and Boussinesq; and the English: Froude, Airy, Stokes, Reynolds, Rayleigh and Manning.
5. Reconstruction of the most powerful lifting machine, with an impulse wheel operated by five men, which appears in the funeral bas-relief of the Haterii family dating from the year 100 AD, discovered in a tomb near to the Porta Maggiore, in Rome (Adam 1989).
6. Some of the most important Spanish dams of this period are: Almansa, Tibi, Elche and Relleu dams (XVI and XVII centuries); the dams constructed by Villarreal de Bérriz (XVIII century) and the buttress dams of Extremadura (XVIII century).
7. Masonry gravity dam, 32 metres high over foundations, constructed in the period 1851–57 for water supply to Madrid.
8. Cyclopean concrete gravity dam, 81 metres high over foundations, constructed in New Mexico (USA) in the period 1911–16.
9. This transition process was far more rapid in the United States due to the greater dynamism of its cement industry.
10. Rubble masonry gravity dam, 86 meters high over

foundations, built on the Salt River (USA) between 1905 and 1911 (Chester 1915).

11. Multiple-Arch concrete dam, 23 m in height, built by the California Eddison Company about in California.
12. Four dams constructed in the valley of the Elan River — Caban Coch Dam, Careg-ddu Dam, Pen-y-Gareg Dam and Craig Goch Dam— and two more in the Claerwen River —-Claerwen Dam and the unfinished Dol-y-Mynach Dam— just before the junction with the Elan.
13. Cyclopean concrete gravity dam, 102 meters high and a world record of the time, was built on the Segre River (Spain) between 1917 and 1920.
14. Cyclopean rubble masonry dam, Max. height 136 ft, built between 1882 and 1889 in Wales.
15. Cyclopean rubble masonry dam, 59 m high, built between 1910 and 13 on the Gallego River.
16. Known as «locomóviles» in Spain.
17. For the construction of the Spanish dam of Camporredondo, 76 m. high and finished in 1930, an auxiliary hydroelectric jump of 150 hp was built.
18. For the construction of the Spanish Jándula Dam, 88 m high and built between 1928 and 1932, an auxiliary cable run of 25 km was needed.
19. Amongst others the Spanish Regato Dam, built in 1897 ;and the American Shoshone Dam, built from 1903–10.
20. Such as India, China and the Spanish Canary Islands.

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Rodrigo Gil de Hontañón's new arithmetical structural rules at the parish church in Villamor de los Escuderos

Sergio Sanabria

In 1638 Galileo's *Dialoghi delle nuove scienze* established the rudimentary foundations of modern structural analysis. Gothic master masons long before had used empirical geometric constructions to determine and preserve useful structural and formal ratios. Before 1538 the Castilian architect Rodrigo Gil de Hontañón devised innovative arithmetical structural rules using square roots and summations, displacing traditional constructive geometry in his practice. Although powerful, Rodrigo's formulae were still empirical, exhibiting no understanding of physical or dimensional units. Rodrigo invented his formulae at the end of an era that accumulated much experimental evidence with little theory to explain it. The formulae mystify modern technicians who expect a physics-based engineering, but Rodrigo's formulae are a century older than Galileo and the birth of modern physics.

The older Gothic spatial geometric constructions used what Lon Shelby (1972) called *constructive geometry*, the manipulation of geometric forms and procedures without understanding the logical structure that would either justify them or prove them inconsistent. Rodrigo's search for meaningful structural ratios used what Charles Sanders Peirce called *abduction* or *retroduction*. (Fann 1970, 5–10) While induction is a search for generalities from specific facts, abduction is a search for a theory from those same facts. The theory need not be «true» or even reasonable, but must try to structure and organize experience, and can be an intermediate step towards a deeper scientific understanding. Rodrigo's structural rules represent a late stage in the development of abductive reasoning in the masonic world. His formulae are more mathematically sophisticated than what 13th or 14th century masons could have produced, but seem grounded on the same body of constructive experience.

In a Baroque architectural compendium of 1681 the architect Simón García from Salamanca transcribed what we have left of Rodrigo's writings. (García 1681; Rodicio 1992) In Simón's chapter 6, 18v-19r, Rodrigo claims to have been puzzled a long time about the correct depth of a buttress supporting an arch such that the depth is neither more nor less than is exactly needed. He asked many Spanish and foreign masters if they knew any such rule, and got only rules of thumb and formulae that did not meet his criteria. Hence he undertook to create some rules that would accomplish this. Seven of his formulae survive, and they give required sizes for piers and buttresses, and the correct weight of a keystone. (Kubler 1944; Hoag 1958; 426–35, 441; Sanabria 1982)

Rodrigo imposed two conditions on satisfactory rule for buttress depths. First, the rule must be general; it must work for any arch. Second, it must give only a sufficient depth, as much as is required to support a given load and no more. Generality and sufficiency were important but uncontested concepts. Rodrigo sought positive results without studying mechanisms addressing his conditions. For example,

sufficiency could lead to a precariously balanced buttress, swaying to any added load. If buttress and arch formed an integral unit, which one would fail first? Would slippage and hinging between voussoirs undermine the arch before the buttress became unstable? Rodrigo mentions a safety factor in 18r, but does not question how much redundancy is needed nor where. The requirement of generality is also problematical, because different arch shapes or voussoir depths affect thrust angles and balance. In Rodrigo's era, the only theoretical study of vault thrusts had been Leonardo's tentative application of Archimedean principles to the analysis of arches and their supports, which yielded no practical results. No satisfactory statement of this problem was published until the end of the 17th century.[1] Rodrigo wanted a synthetic formulation, a proto-mechanical recipe like the gothic geometric constructions, or alchemical recipes for gold, that would give reliable values. Despite his lack of conceptual tools, at least two of his rules suggest some experimentation. (Sanabria 1982, 289)

Rodrigo began his career completing unfinished projects of his father, the great Late Gothic master mason Juan Gil de Hontañón, who died in 1526. Among these was the sanctuary of the parish church of Nuestra Señora de la Asunción in Villamor de los Escuderos, executed between 1526 and 1536. (Figure 1) On June 6, 1526, some three months after Juan Gil's death, Rodrigo contracted to continue the work following his father's specifications. In a letter of intent of September 3, 1529, he promised to complete the vaults by June 1531. (Casaseca 1989, 130–3) As in many contracts of that time, the builder absorbed all construction costs to completion. Only bidders with substantial resources or backers, experience, and a record of success could qualify. Rodrigo posted a bond with three guarantors on September 10, 1529. Obviously he was no newcomer, but a young principal of a well-established business. In 1536 Rodrigo completed work on the sanctuary, and after a contested appraisal that led to a lawsuit, the church paid for this campaign late in 1537. (Figure 2)

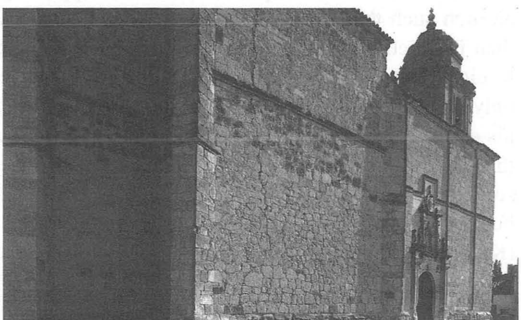

Figure 1
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. North flank of church, showing the rubblework sanctuary and north transept in the left foreground, and the ashlar nave to the right. Note that the massive nave buttresses project only slightly beyond the chapel walls

Figure 2
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Sanctuary, designed by Juan Gil de Hontañón before 1526, and executed by his son Rodrigo Gil, between 1526 and 1536

Despite the conflict, Rodrigo remained master of Villamor until his death. In 1538 he started work on the nave of the church, altering his father's design in part by using one of his new structural rules for piers. He visited Villamor for fifteen days in May or June of 1540, as recorded at the archives of the cathedral of Salamanca, and appointed Gonzalo de la Atalaya as his *aparejador* (general contractor). (Chueca Goitía 1951, 147) Construction was patronized by Antonio del Aguila, bishop of Zamora 1546–60, whose coat of arms appears in the north portal and the *hornacinas* (chapels between buttresses). Rodrigo's nave is as high as its hornacinas, an unusual variation of a hall church, repeated later at his churches at Santa María de Guareña and the chapel of the Hospital de la Misericordia in Segovia. (Figure 3) The nave walls are of ashlar, contrasting with the rubble of the sanctuary. Its massive buttresses are nearly flush with the exterior wall.

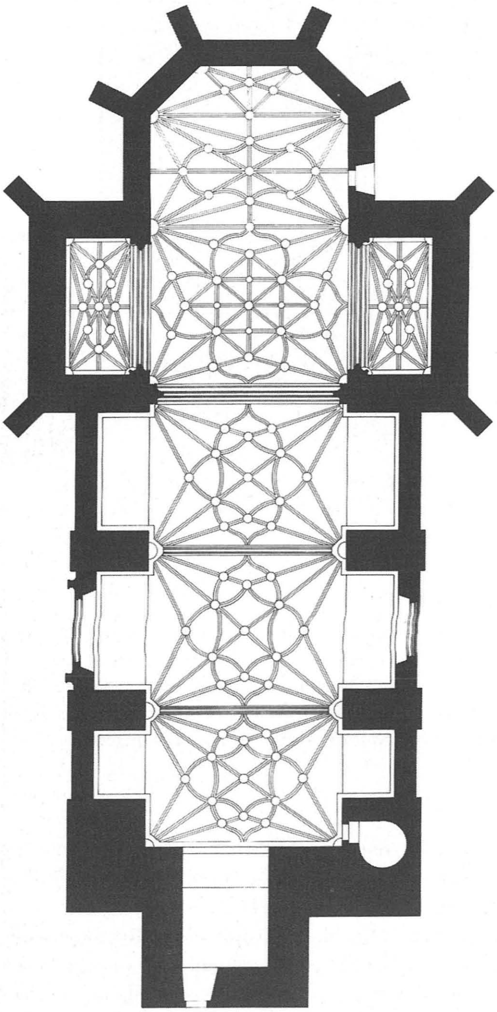

Figure 3
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Nave, designed and executed by Rodrigo Gil de Hontañón after 1538. Note the massive butresses separating the chapels, whose height is the same as that of the nave

The plan of Villamor resembles generically two plans in Simón García's book, the Third Temple Design by Human Analogy in 4v and the Fifth Geometric Temple Plan in 14v-15r. (Figure 4) The plan of the nave is irregular, its three bays are approximately 5.83, 6.75, and 5.85 meters long, respectively.[2] Thus no exact relationships hold between it and the formulaic plans in Simón García. The nave is as wide as the sanctuary, approximately 8.40 meters. The *hornacinas* are about 2.20 meters deep. Their depth seems unrelated to the nave width, and was determined instead by the pier formula. Structural sizing governed spatial ratios in this classicized gothic construction. Clearly Rodrigo had invented his new formulae by this time, dating much of his literary output to the beginning of his career.

Wall buttresses between the *hornacinas* are thicker than transept walls. These buttresses differ clearly from those of the sanctuary, and are double squares in plan. They measure 3.35 × 1.70 meters, which equals 4.01 × 2.03 *varas de Castilla* of .836 meters, or 12.02 × 6.10 Castilian feet of .279 meters. Their size and double square proportion follow a structural formula discussed at length in Simón García's *Compendio*, first in chapter 2, 5r-5v, used while designing a church, and again in chapter 6, 17v, where it is explained. The formula yields the width W of the buttress at the springing of the vault. The plan of the buttress is preordained to be a double square, so its depth is $2W$. Rodrigo specifies a complex operation:

$$W = \frac{1}{3} + \sqrt{H + \frac{2}{3} \sum P}$$

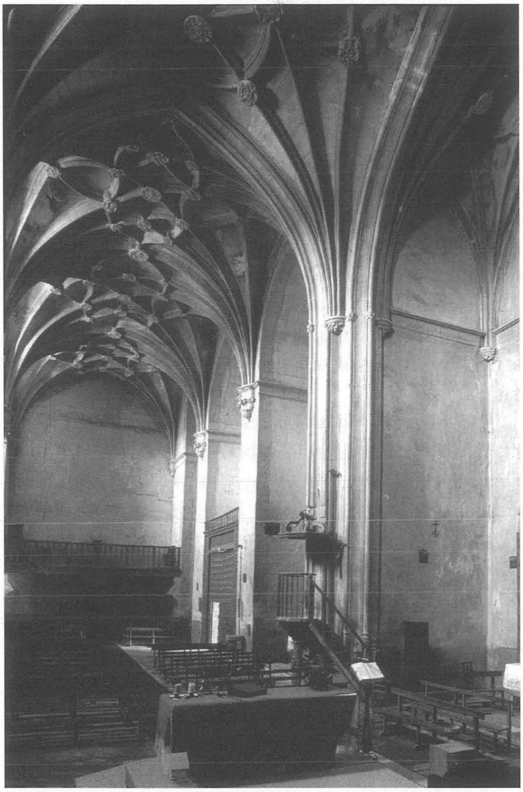

Figure 4
Villamor de los Escuderos. Parish church of Nuestra Señora de la Asunción. Plan. Redrawn after an original survey by Marco Antonio Garcés and Luis Navarro

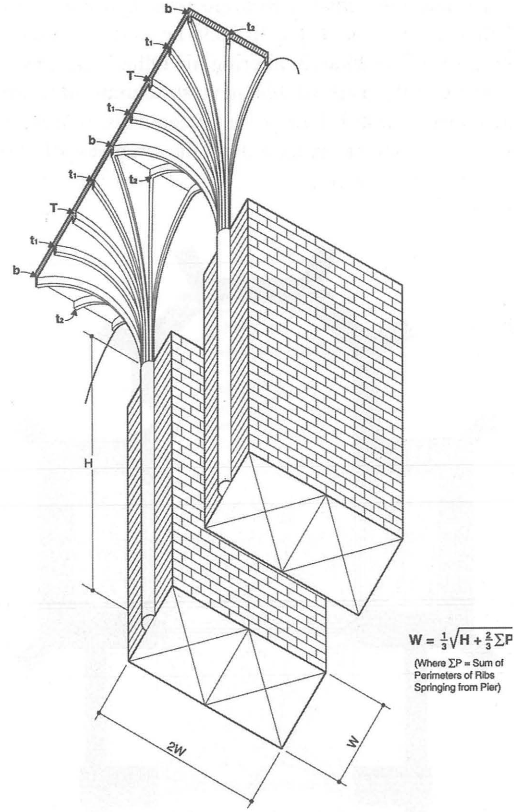

Figure 5
Rodrigo's second arithmetic formula, given in Simon García's *Compendio,* 5r-5v, and 17v. Because of the square root operation, the formula yields proportionately larger buttresses for larger units of measurement. It appears to have been calibrated for Castilian feet of .279 meters

where H is the height of the buttress to the springing and $\sum P$ is the sum of the perimeters of all ribs converging on the buttress, whether transverse, diagonal or tiercerons, measured from the springing to their respective keystones, usually a quarter circle. (Figure 5) At Villamor the height to springings is about 9.8 meters = 35.125 feet = 11.724 *varas*. The sum of perimeters of the five ribs is about 28.2 meters = 101.075 feet = 33.736 *varas*.

That this formula was a novelty in Spain is clear from the awkward, painfully bloated and thick buttresses creating wide expanses of unarticulated walls. It is possible but unlikely that Rodrigo knew and tried to emulate either ancient thick Roman walls, or Francesco di Giorgio's structural formulae, apparently reused by Bramante in the Roman High Renaissance. (Betts 1993) A more likely possibility is that he misapplied the very rule he invented.

Rodrigo's formula is dimensionally inconsistent, expressing length as the square root of length. This means that results change depending on the units used. Results using *varas* will differ by a real factor of $\sqrt{.836/.279} = \sqrt{3} = 1.73$ from results using Castilian feet in the same formula. Normally Rodrigo specified dimensions in feet. Using feet his formula yields buttresses of 1.88 × .94 meters, not the dimensions of nave buttresses, but closer to those in

Juan Gil's sanctuary that measure approximately 2.5 × .9 meters. Using *varas* the formula yields buttresses of 3.26 × 1.63 meters, or 3.90 × 1.95 *varas*, very close to those built. The small upward adjustment to 4 × 2 *varas* was reasonable, although we cannot be certain as to the exact values used for the sum of perimeters of ribs, which could throw the results off by a few percent.

Neither Rodrigo nor his *aparejador* could have known that the formula garbled units of measurement and so was sensitive to the units used. By specifying building dimensions in *varas* instead of feet the buttresses were inadvertently enlarged 1.73 times. Whether the architect or the *aparejador* was responsible is not clear, but in one of his infrequent inspection visits to the site, Rodrigo must have discovered that this was an unusually massive structure by the standards of Spanish gothic construction. He made no obvious corrections to the building in progress, which would have been difficult. Villamor was the most massively buttressed building in Rodrigo's work, proportionately heavier even than the cathedral of Salamanca. He learned not to trust his rules blindly, a lesson that young designers relearn to this very day.

Notes

1. The earliest theoretical analysis of arches and their abutments was in Philippe de la Hire, Traité de Mécanique, published in Paris in 1695, using funicular force polygons. In 1730 Pierre Couplet advanced the analysis by determining the permissible limits of lines of thrust, graphic depictions of summed forces. Leonard Euler's 1740s work on elastic curves ushered a new horizon. See Timoshenko, History of Strength of Materials, chapters 2, 3; Jacques Heyman, «Couplet's Engineering Memoirs, 1726–1733», Arches, Vaults and Buttresses, 221–44.
2. The church was surveyed in 1984 by Marco Antonio Garcés and Luis Navarro. Copies of their drawings are at the Archivo del Servicio de Restauración de la Junta de Castilla y León in Valladolid.

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Materials & architectural details in the architecture of the Modern Movement in Sardinia

Paolo Sanjust

It should be stated at the outset that every type of material expresses —or rather invokes— a formal world that is consentaneous and homogeneous to it. Brick, stucco, wood or stone live «de facto» within a formal concordance and, above all, they proceed at the same pace within the world of traditional work. The labour of the metal worker is matched by the labour of the mason, of the paver or that of the carpenter. Thus our age, whose crisis we are only now starting to realise, may also be categorised under the name of age of consentaneous expressive materials, those, that is, which pass through the filter of manual labour, inheriting its insuppressible hallmark of uniqueness. ... A world thus constructed and so slowly settled is obviously destined to crumble when it is called upon to face up to the use of new materials; since the latter, in their turn, carry internally and therefore promote and require a formal vocation of their own. In the same way, they require different work, different trades, other working languages, other words. ... We are, indeed, within that silent space, in truth intense and filled with noise, which opens between intuition and result: we are, that is, right in that space which idealistic Italian tradition has almost always kept hidden, firstly denying to the notion of «mechanical» the prestige reserved only to the «liberal»; subsequently extending out of proportion the borders of the intuitive act and consequently narrowing the bounds of the executive and operational act. (Emiliani 1981).

Investigating the link between constructive details and architectural result means attempting to «follow the path which starts from the consideration of materials and, passing through techniques, methods and crafts wishes to reach the history of art ... » (Emiliani 1981).

In his inspiring work, Andrea Emiliani challenged historians to try and adopt also the viewpoint of the *construction* (besides that of the *project*) to achieve deeper and more complete awareness of the history of architecture. Emiliani quotes Focillon who affirmed that «materials involve a certain destiny or, rather, a certain formal vocation»; but he also wrote that «materials are not interchangeable but techniques penetrate each other and, on their borders, interference tends to create new materials». The latter quotation may serve as a key to understanding this paper, which attempts to analyse some forms of modern architectures in a land dominated by a strongly marked tradition, as was Sardinia in the first half of the 20th century. This contribution aims at identifying that very interference between «text» and «context», i.e. between traditional techniques and materials, and the innovations introduced by the modern project which, in its original contexts, expressed itself in far different materials and techniques.

But even a broader interpretation of Focillon's phrase may help us focus on the more general theme of this Congress, by highlighting the need for an approach that cuts across different areas of study, including the history of techniques, structure and material analysis, the history of architecture etc.,

leading us to develop an *inherently interdisciplinary history*, through the effort generated by each area of study in its intermingling with other areas, rather than the flowering of many sectoral studies in the perspective of an always sought after (but rarely achieved) form of interdisciplinary study.

The Modern Movement appeared in Sardinia in the early 1930s, thanks to the foundation of new cities: Mussolinia (Pellegrini 1998, 1999), Fertilia (Peghin 2001), Carbonia (Pisano 1998), and Cortoghiana (Sanna 2000). The architects and engineers called upon to draw up these city-founding projects were well versed in the use of modern materials (reinforced cement concrete, iron sections for casings and frames, linoleum for flooring and wall facing, cladding bricks etc.). However, due to the political and economic circumstances of Fascist Italy (firstly the sanctions imposed on Italy by the League of Nations, then, from 1936 onwards, the *autarchy* policy), they were compelled to limit the use of these modern materials and turn to traditional techniques and local materials (or at least materials produced in Italy), and above all to reduce drastically the use of iron, which came from abroad, in reinforced concrete structures.

This particular state of affairs contributed to the development in central Italy and the Italian islands of a modern architecture which, with respect to European architecture, was marked by the prevalence of *masonry* technologies, as a distinctive formal characteristic. This cross between modern design and the local contexts firmly rooted in traditional materials and techniques led the best designers to bend to modern design requirements those materials (stone, wood, lime mortars and plasters) and those types of manual works (load-bearing walls, wooden roofing structures, plasterwork dressed in place, stone cladding) deriving from a tradition stretching back many centuries.

The GIL building at Arborea, by G.B. Ceas (1933–34) (Pellegrini 1998, 1999, Sanjust 2002)

This building, about 10 m high, is based on a 4.5 m structural module. Its L-shaped plan has its joint in the square atrium with at the centre a round pool which collects rainwater from the roof. The latter is supported by a series of reinforced cement concrete beams which rest on a circular architrave, born by

Figure 1
View of the building site (1934)

eight pillars clad in solid brick in stretcher bond courses. The two arms of the «L» are formed by the covered gymnasium and the open-air swimming pool (8.70 × 20 m).

Another «L» shaped body, 5.5 m high, partially linking the South and East fronts, houses offices, a library, locker rooms, toilet facilities and a storage area. This body is marked by cladding in stretcher bond courses of full bricks (24 × 12.5 × 6 cm), and by a ribbon windows with white wooden frames. On the main front, framed by splayed brick walls, is set the main entrance, leading to the atrium with its circular pool by means of a paved stairway with bricks set in herring bone design.

The main body of the gymnasium has six round windows in its southern exposure, and the same number in the northern, from which a further three doorways lead down to the sports field by means of a staircase with six stairs in edgeset bricks. In the back wall of the gymnasium, facing west, there is a large set of windows consisting of a grid of five by four rectangular windows, in varnished wood, with horizontal hung opening. The gymnasium has a flat roof in reinforced cement concrete with two skylights adding to the ventilation and lighting provided by the round wooden windows; these windows, 1.5 m in diameter, are horizontal centre hung so that the top

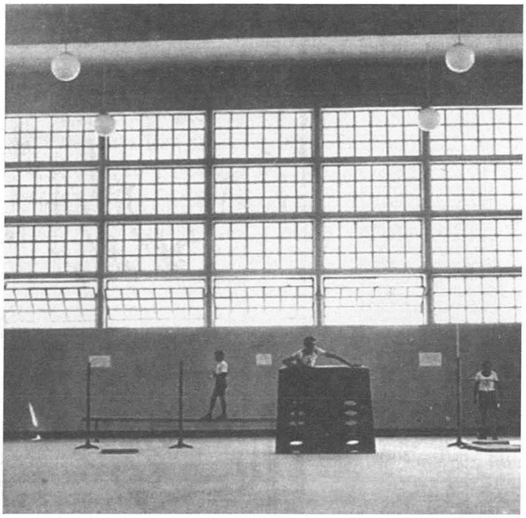

Figure 2
The large windows of the gymnasium

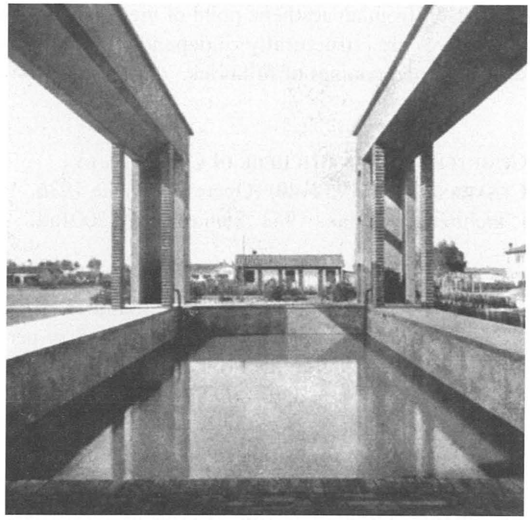

Figure 3
The portals framing the swimming pool

half can be opened and are mounted on an ring of head-set bricks. The structural system is made entirely of reinforced cement concrete and consists of a series of portals, with 4.5 m centre distance, each consisting of two pillars measuring 40 × 84 cm and a beam with «I» shaped section, 150 cm high, with a 18 cm wide core and 40 × 40 cm heads, linked by secondary beams, set with 2.70 m centre distance between, 15 cm in width and of height varying between 23 and 40 cm at the bearings. The roof slab has a design thickness of only 8 cm; beneath it, 80 cm from the intrados of the main beam there is a ceiling consisting of a main wooden beam frame (section 11 × 13 cm) and by a secondary wooden strip frame to which the furring is fixed. In the first area of the gymnasium, near the entrance atrium, there is a grandstand, consisting of floor slab resting on two concrete beams (section 25 × 35/50 cm), originally accessed by means of two staircases contained in curved housings, clad in full brick set in stretcher bond pattern, which today have been demolished.

The open-air swimming pool is inserted in a sort of scenic background consisting of a full height exedra, adjoining the atrium with the circular pool, which extends in two large portals.

The two beams which form each portal, set at a height of 8.3 m, about 22.6 m long, set 2.5 m apart and with a clear span of 18 m, are constructed in reinforced cement concrete, with closed head, while the lower side opens into an inverted «C» bay shape. The intrados of the beams is barrel vaulted by means of a structure in running wooden strips onto which a plaster-supporting net is fixed. The structure is set, by means of sliding rollers, on an independent body consisting of six pillars, four of which form a composite pillar, forming the continuation of the

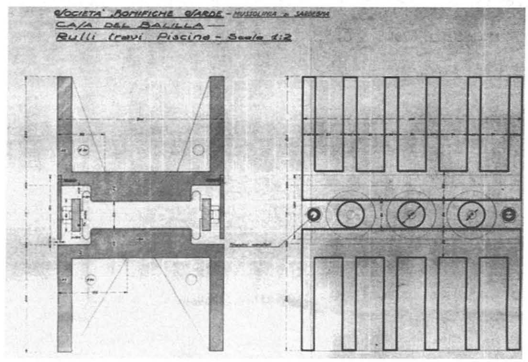

Figure 4
A detail of the sliding trucks of the beams of the swimming pool

beam itself from an aesthetic point of view, while the other two are structurally independent, clad in stretcher bond courses of full brick.

CEMETERY OF SAN MICHELE IN CAGLIARI, BY CESARE VALLE (1934–40) (Opere Pubbliche 1936, L'architettura Italiana 1941, Sanjust 1999, 2001a)

The central portion of the building leading into the cemetery consists of an ample chamber (the Memorial Chapel) of square ground plan, 15 m per side, covered by a reinforced cement concrete dome. It is accessed through a wide main staircase and two large lateral halls, which in turn lead to the two porticoes that open onto the main open area of the cemetery and link the Memorial Chapel with the two side buildings used for various service purposes. The frame structures of these buildings are in limestone and cement mortar, whereas the pillars of the porticoes and the roofs are in reinforced cement concrete. The roof of the Memorial Chapel is constructed in the following manner: a series of beams set out in a square mesh links the drum to the supporting walls; on the drum are set eight beams of varying section (in the form of a rampant arch) linked at the key by an open ring; the vaulting cells are formed of thin concrete slabs. The base course and the pillars are clad in large slabs of travertine stone (6 cm thick) fixed with two hidden joints for each slab,

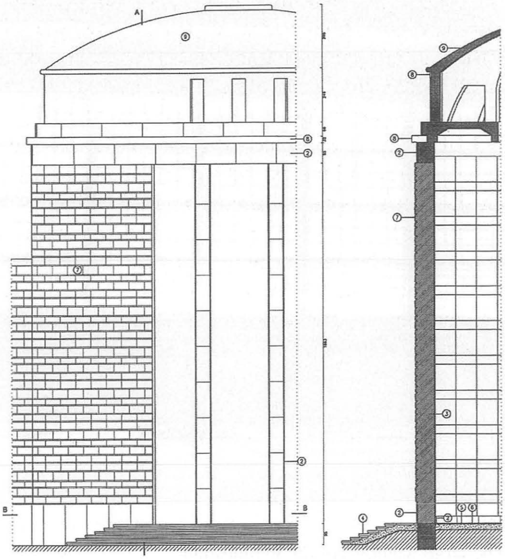

Figure 6
Relief of the Memorial Chapel

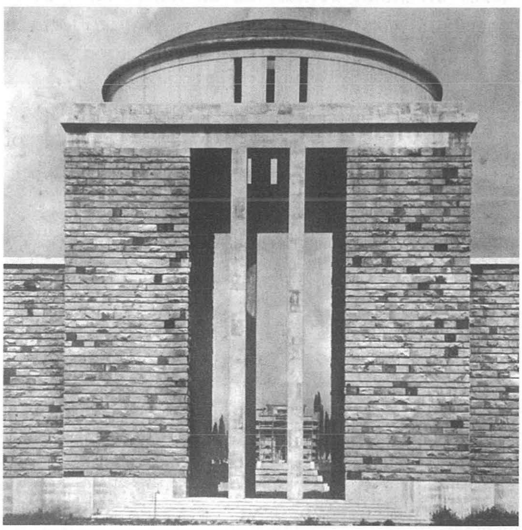

Figure 5
The Memorial Chapel

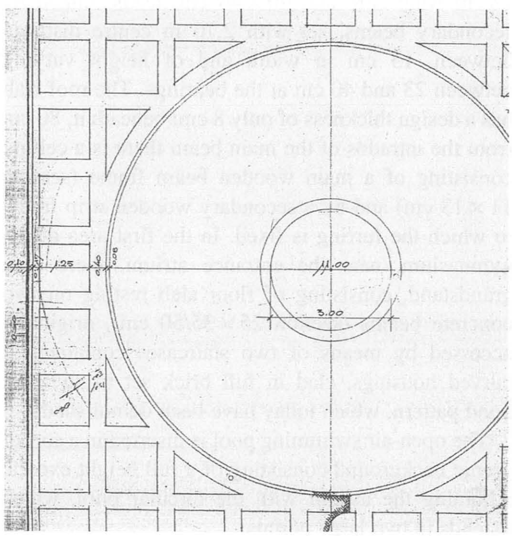

Figure 7
Detail of the plan of the Memorial Chapel dome

set diagonally. Flooring of the Memorial Chapel is also in slabs of travertine stone (measuring 80 × 160 cm) with trachyte insets. The porticoes are floored in small rectangular grès tiles. Plasterwork is of the Terranova type, bordered and coloured; externally in red and internally in blue, while the intrados of the cupola is cobalt blue. The door and window frames are in iron sections. Cladding of the building is in trachyte stone from Serrenti in courses between 20 and 40 cm in height, thickness 35 cm, alternating with 5 cm joints, obtained by dressing the stone blocks; cornices and copings are in travertine blocks (section 18 × 60 cm).

MONTUORI'S PROJECTS FOR CARBONIA (1939–41)
(Sanjust 2001)

In the construction of Carbonia the use of local, traditional materials and techniques was a planning imperative right from the start: « . . . projections and bold structures were almost entirely abolished; roofs and lintels in reinforced cement concrete were calculated on the basis of a ratio between the stress of the cement concrete and the iron such as to reduce the use of the latter as far as possible. The use of lumber was also contained within rigid limits. It should be stressed that the structures were chosen with care with an eye to utilising, as far as possible, local materials; thus we see wide use of stone and minimal use of brick; dressed stone, even when intended for decorative purposes, was to be obtained from nearby quarries» (Pisano 1998). Within these constraints in technical and economical resources a line of research was developed which saw Eugenio Montuori develop his projects around the use of trachyte in pure volumes, stereometrically associated with plastered volumes, or in façade and counter-façade sections adjoining plasterwork structures. This line of architectural research was just hinted at in some of the projects drawn up over a very brief period between 1937 and 1938 and realised equally rapidly for the inauguration of the city in December 1938. But this research was further developed starting from 1939 with the project of the Caserma della Milizia, and matured in 1940 with the high-intensity labourer housing project known as type B1, and in 1941 with the project for the blocks of flats with galleries.

Figure 8
The staircases supported by trachyte sections

The *B1 type* block, consisting of 48 accommodation units, has a linear development, on four floors with three staircases, each with landings leading to four small apartments per floor. The flats are of two sizes: 51 sq m with two bedrooms, and 38 sq m, with single front and one bedroom. The staircases are external, with a single flight of steps set parallel to the building and a return walkway in the form of a gallery; this latter element is inserted in a deep common loggia looking onto the street, set into the volume of the building. The distinctive element of this building, as regards its type and distribution features as well as its compositional and formal aspects, is this system of loggias and external staircases, in which a decisive role is played by the choice to realise vertical structures with trachyte-faced sections, with passage through round arches; the flights of stairs are in cement and the steps are in trachyte. The result is a strong chromatic contrast between the red of the stone and the plastered sections.

The 18–flat block may be seen as the development, as to type and architecture, of type B1; from the point of view of typology, the choice of the gallery system, well resolved also as regards aspects linked to introspection, allows Montuori to overcome the problem of the single front exposure which we find in type B1. From an architectural point of view, the trachyte sections, which characterised the loggias of

Figure 9
View of the gallery

type B1, here become a sort of counter-facade system, set against the habitation volume, which contains the galleries. This project, which was never implemented, can probably be seen, in the example of Carbonia, as the best expression of the results of research into the feasibility of Modern design in contexts linked to traditional building methods.

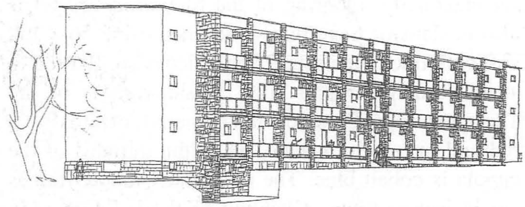

Figure 10
The trachyte wall sections and the gallery system

Saverio Muratori at Cortoghiana (1940)
(Sanna 2001)

The example of Cortoghiana, a mining village in the Province of Cagliari designed by the young Muratori, tells the story of the extraordinary meeting between the desire to implement some form of European Modernism and the concrete reality of a country which was backward from a technological point of view and which was beginning, in an autarchic regime, to sink back into its past. Cortoghiana was planned round an extraordinary square measuring about 200 × 50 m, with porticoes on all sides, which forms an «L» shape with a small square of about 40 × 70 m onto which opens the Church. A sort of modern metaphysical Venetian Piazza S. Marco which places itself in comparison —and wins the battle— with the more traditional squares of the other fascist new towns built in the same period. And yet it

Figure 11
View of the square in the 1940s

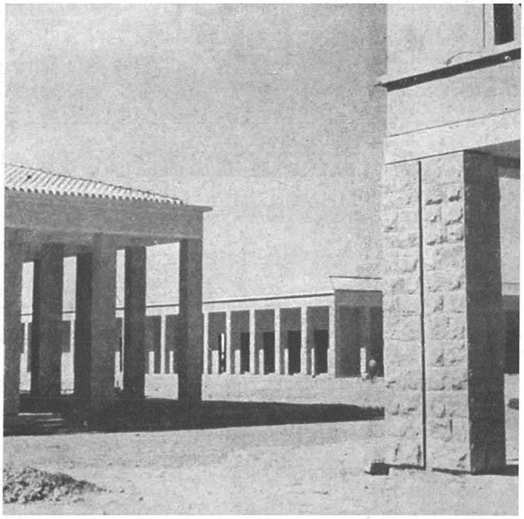

Figure 12
View of the period

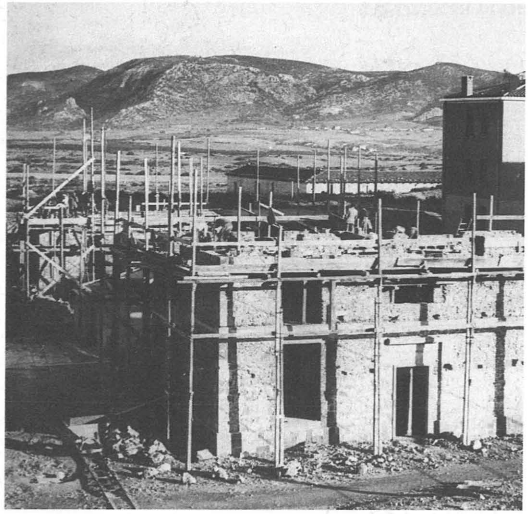

Figure 14
View of the building site

is entirely created with the masonry technologies of Italian tradition: the pillars of the square's portico are in load-bearing trachyte stone, as are the walls of all of the buildings; the roofing structures are generally in wooden trusses covered with bent tiles; for the elevated floors reinforced cement concrete is used, the only concession to a modern material which had by then become of common use on Italian work sites (a material, moreover, which could be easily assimilated into the masonry tradition), but no overhang was possible, in view of the lack or iron, and neither was any large-size opening.

As may be seen, during an initial period, which lasted at least until 1936 and coincided with the opening of the Fascist system towards modern architecture, planners were able to experiment with new forms and new materials. From 1936 on, with the beginning of the crisis, the sanctions of the League of Nations imposed on Fascist Italy, and marked involution in all sectors of Italian life (the shameful racial laws date from the same year) in architecture too it became impossible to experiment with modern materials, and only thanks to the capacity of building designers were architectural projects worthy of their time achieved, albeit realised exclusively with the materials and techniques of bygone days.

Figure 13
View of the portico at the present time

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First applications of reinforced concrete in Sardinia The «Porcheddu Company Engineer G.A.» and his plan archives

Antonella Sanna

Plus d'incendies dèsastreux
F. Hennebique

First Applications of Reinforced Concrete

In order to validly reconsider the phases of development and diffusion of reinforced concrete, first of all, it is necessary to agree on definitions; to this end, it is possible to refer to the definitions of Mörsch[1] and Le Corbusier,[2] who, in different periods and from the opposite perspectives of calculation theory and architectonic practice, both agree in underlining that the essential characteristic of the new technique does not actually consist of pairing off iron and concrete *tout court*, but rather of the rational distribution of static functions between the two materials according to their different aptitudes. These authors, therefore, point out their awareness of one necessary factor: the collaborative behaviour of both materials, which constitutes an inescapable fact in order for reinforced concrete to be recognised as such. However, the mature form of the new construction technique is preceded by numerous attempts and intuitions, which, although not rigorously adhering to the definition of reinforced concrete, have nevertheless constituted its fundamental assumptions. In fact, it is in the scientific and economic environment that took shape in Europe after the Industrial Revolution, that numerous patents for small construction works in «cemented iron»[3] were taken out, this name reflecting that of «reinforced concrete», arises from the differences in the proportions and in the role of the two materials: indeed, they consist of metal mesh, essentially self supporting, upon which quite a dry layer of grout is spread, with the prevalent function of abutment stone, but not contributing to resistance. In 1890, the

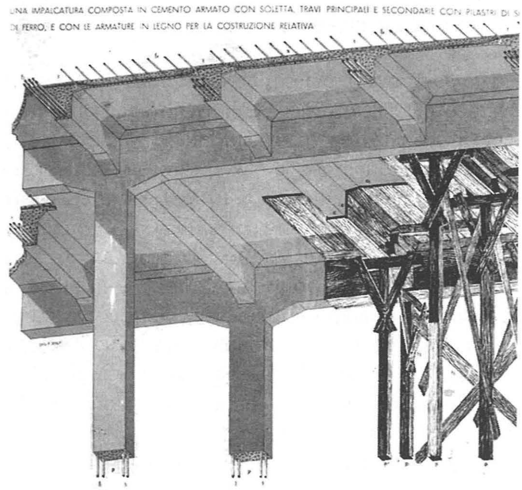

Figure 1
Typical reinforced concrete structural system, consisting of pillars, main and secondary beams and slab, constructed according to the Hennebique patent. (Formenti 1893)

Cottancin system for reinforced beams cast in disposable moulds in hollow bricks, still represented a hybrid between medieval masonry ribs and the framework in reinforced concrete. Shortly after wards, it was thought that the iron-concrete combination could be used for small slabs,[4] marking the first turning point towards real reinforced concrete, as defined above.[5] However the authentic technological revolution arrives with Françoise Hennebique, who, between 1892 and 1898, invented, improved and patented in France a new construction system which rationally combines the ability of concrete to resist compression and that of steel to resist tensile stress. This new system also eliminates the danger of fire and permits more audacious construction and longer spans, with load-bearing structures characterised by minimum encumbrance.

The innovation in respect to Hennebique's contemporaries, clearly visible in the drawings of that period, is the understanding of the relationship between the arrangement of reinforcement and the distribution of internal stress, leading to a particular lay-out of the lower iron rods, some of which are bent to bring them to the upper edge near the fixed joint, where inversion of the bending moments takes place and the action of iron is therefore necessary. In addition to this innovation, we should add the contribution, made by the 45° —inclined portions, to the absorption of shearing stress, to which the U-shaped flat iron stirrups also contribute.

His fame as the «father» of reinforced concrete is rightly justified by the astonishing similarity between his original drawings and the present shape of the reinforcements, by the fact that he was the first who thought rationally in terms of «load-bearing skeleton» and «frame» and by the fact that he understood, without giving a scientific explanation but proposing remarkable practical applications, the existence of plastic flow in addition to the already-known elastic strain. The great success of the reinforced concrete technique, once initial mistrust was overcome, all is above due, in addition to the intrinsic qualities of the material, to the popularizing and promotional activities of Hennebique himself (Delhumeau 1999). His activity was not only confined to the commercial diffusion of the patent, but more generally, to advertising the general virtues of the system. Thanks to his strong company structure, he managed to organise conferences, publish reviews and above all create a network of agents and distributors all over the world that produced a substantial number of constructions and experiences. We can affirm that modern reinforced concrete is definitively defined by the Hennebique system and from now on research will be directed essentially to improving quality and reducing costs, without introducing substantial changes in the system of pillars, beams and floors.

ENGINEER G.A. PORCHEDDU AND HIS COMPANY

Although he has been forgotten in present-day Sardinia in the first few years of the last century, Giovanni Antonio Porcheddu merited international fame (Sole 1976). He was born in Sardinia in 1860 and died in Turin in 1937. Coming from a humble family, like Hennebique, he began working as a hod man in building yards, where he acquired the practical skill that will be very useful when, during is first years of activity as agent for the French patent, he himself did calculations and even trained the first workers in the yard. In 1890, he got the first of three degrees in engineering and, only four years later, became Agent and General Dealer for Northern Italy of the Hennebique system.

As word of the daring constructions of the Porcheddu Company spread, a chain reaction was triggered which, passed by word of mouth among the industrialists of the country and fomented by the publishing of his works in the technical journals of

Figure 2
Porcheddu's label used to mark drawings and calculations. Archivio Porcheddu di Torino, henceforth APT

that period, would rapidly bring about an increase in orders and the construction of more and more audacious structures. Starting from the end of the first decade of the last century, the influence of the Porcheddu Company spread outside Northern Italy and in 1914 the whole peninsula considered him the only agent of the Hennebique system. In addition to the French system, his company also used other patents such as Siegwart beams and foundations with Compressol piles; he also invented a special section of reinforcement irons which increased ahderence to concrete. Among the thousands of jobs carried out by the Company, some record-breaking structures which brought Porcheddu international recognition stand out, among them the grain silos in Genoa, the biggest structure of that period entirely built in reinforced concrete, and the Risorgimento Bridge in Rome, with the largest opening covered by a single span up to then. To that, we can add other buildings, not record-breaking but just as famous as the previously-mentioned ones, like the Fiat Lingotto factory in Turin, the Assicurazioni Generali Palace in Milan, the hangar for dirigibles in Parma and the rebuilding of the San Marco bell tower in Venice.[6]

He had the merit of foreseeing the enormous potentialities of the new building system, also taking into account the abundance of concrete and the scarcity of iron in Italy which made the affirmation of iron and glass structures problematic, all factors leading to the success of the new reinforced concrete technique. Given the still hybrid nature of construction and the yard, the Porcheddu Company intervened only in the planning and building of structures in reinforced concrete, depending for all remaining tasks on the contract holders and those responsible for the work as a whole. Porcheddu agreed to provide specialised workers to coordinate the assembly of moulds, the folding and placing of the rebars and the casting of concrete; the reinforcement came directly from the ironworks of the company in Genoa and the concrete was also made on the mainland. Local firms had to provide water, aggregate, wood and non-specialized workers to assist with the concrete castings and assemble and disassemble the moulds. In comparison to masonry buildings, this type of job organization, among other things, made the work faster and more rational. It was, in fact, possible to carry out all necessary work contemporaneously, in different areas of the building, applying modern optimization theories of productive processes through the fragmentation of various tasks.

When building in reinforced concrete became required by national law, sole rights were lost; however, the experience accumulated by the Company was such that for many years it continued to hold a virtual monopoly, even in view of the empirical and non-rigorous nature of calculations, which often led to simplifications or applying hypotheses on the behaviour of structures that only long experience could justify. The success story of the Porcheddu Company ended in 1933, four years before Porcheddu's death, due to the widespread use of reinforced concrete, rendering problematic the survival of a company whose strong point was its exclusive practical know-ledge.

The Porcheddu Company and Sardinia

Whilst Porcheddu improved and consolidated his firm in Northern Italy, in Sardinia authentic industrial development had not yet started, due principally to geographic isolation and a still mostly agricultural economy.[7] Entrepreneurs coming from Liguria and Piedmont were the first to establish their factories, linked mostly to the processing of cereals, in Sardinia. Thus it was that in 1904, some years after the building of a mill for the Italian Semoleria at Sampierdarena (near Genoa), Porcheddu was given the order, by the above-mentioned entrepreneurs, to construct a similar building near the port in Cagliari.

The appearance of the Porcheddu Company in Sardinia allowed him to begin creating a commercial network, basically linked to the supplying of yard materials (Boggio, Di Felice and Sapelli 1995; Del Piano, Fadda and Sirchia 1995). Moreover, in the wake of the construction of the Semoleria in Cagliari, news of the advantages of the new technique spread among the middle class, and reinforced concrete began to be used for the new factories, as well as for exclusive homes. Porcheddu's activity was supported and promoted, on the national level, by the Banca Commerciale Italiana, a Milan-based bank which would provide financial capital to promote the development of the transportation system and the huge inland hydraulic installations that, along with the mining industry, were of particular interest to the Company. However, the beginning of the First World

War on the one hand, and changes in the Sardinian banking system, with the Credito Italiano replacing the Banca Commerciale and the consequent rise and decline of the firms connected to them on the other, contributed to a decrease in orders for the Porcheddu Company and smoothed the way for Ferrobetòn, a Rome-based firm also specializing in reinforced concrete, which constructed the extensive hydraulic and electrification works in the Tirso river basin.

In Sardinia, the rise and fall of the Porcheddu Company was relatively rapid, although characterized by work that aroused great interest in local public opinion and contributed to dispelling mistrust of reinforced concrete. A list works ranges from the industrial sector, to residential areas and service structures, even taking on historical buildings, like the roofing of the Bonaria Basilica and the choir stalls in S. Lucia Church.[8]

The man who more than others linked Porcheddu's business to the Sardinian productive and economic environment was engineer Riccardo Simonetti[9] who took his degree in Turin, like all the other Sardinian engineers of the time, in 1898 and, once he came back to the island, soon entered the promising new field of reinforced concrete buildings. Only in 1906 did Simonetti and Porcheddu meet; the former designed the Picchi house in Cagliari, while the latter produced the flat slab floors in reinforced concrete. In business correspondence preceding this date, it was Porcheddu who, from Turin, dealt with Sardinian customers, while in 1909 Simonetti himself gave orders and instructions for structures in reinforced concrete, a sign that the young engineer was already an expert in the new construction system and, above all, enjoyed Porcheddu's confidence. Only afterwards will he be indicated as the local representative of the Turin-based Company. Simonetti's role is not only that of building supervisor, but above all that of dynamic dealer. This is demonstrated, for example, by the industriousness with which he promoted, among the Mercedari Fathers, the system of reinforced concrete for the Basilica of Bonaria dome in Cagliari, overcoming the opposition of some believers (Sulis 1935, 166–167), or by the way in which he tried, although without success, to ensure Porcheddu's participation in the huge hydraulic installations on the Tirso river.

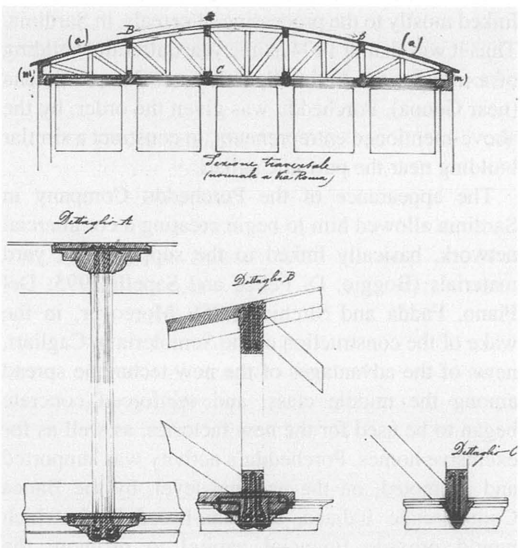

Figure 3
Reinforced concrete frame proposed by Porcheddu for the glass roof in the New Town Hall Honour Court in Cagliari, 1906. (APT)

Archives and Work of the Porcheddu Company

We know how every architectural work originates and is transformed in the course of time, often leaving a documentary trace of the plans, construction and of its evolution; this is even more true as regards twentieth-century architecture, for which the availability and completeness of archives often offers vital information for research. The precise working methods and the rigorous organization of the Porcheddu Company, directly modelled on the *maison* Hennebique, has led through the years to the accumulation of numerous important documents, meticulously catalogued and preserved.

In the Department of Engineering of Territorial and Building Systems (DIS ET) at the Polytechnic in Turin, hundreds of files concerning 2600 projects carried out by the Porcheddu Company between 1895 and 1933[10] can be consulted. The archives, presumably complete, are organized according to geographical areas and, secondarily, in chronological order; works are concentrated principally in Liguria, Piedmont and, to a lesser extent, in Lombardy and Veneto. There are few constructions in the Rome

Figure 4a
View of the Risorgimento Bridge, before striking the reinforced concrete centres, Rome, 1911. (APT)

area, but among them, there is the Risorgimento Bridge on the Tiber, certainly the most innovative work from the technological point of view, where it seems that Hennebique, collaborating on the project, understood and used the existence of plastic flows, until that time unknown in classical theory.

In addition to the rebuilding of Messina and Reggio Calabria after the earthquake in 1908, Sardinia and the colonies in North Africa complete the list of regions «conquered» by the Turin Company.

In the Turin Polytechnic archives we find, for each order, all the documents regarding the carrying out of the work and the business dealings between clients, planners and the Porcheddu Company: architectural plans, calculations for the reinforced concrete and orders for the reinforcement, various business correspondence and contract drafts, all preserved and neatly subdivided in to files. However, the most important documents useful in understanding the inner composition of structures are either missing or very rare: the executive designs of the iron bars, sent to the yard for working, are very rare among the archive documents. In any case, we not only have technical information regarding calculation methods and the construction techniques of structural elements, but the economic and industrial situation of the time also emerges in the background.

Together with the archive documents, witnessing to the attention paid by the company to yard documentation, above all for the most difficult project, there is a rich photographic repertoire. This material also permits very useful interpretation of manufacturing processes and of the inner structure of work, that principally in the initial period, systematically masked the new construction system, which, on the contrary, photographic images of the yard unavoidably reveal.

Among the work that Porcheddu did in Sardinia, we have decided to illustrate two projects: the milling factory for the Semoleria Italiana and the roof of the Bonaria Basilica, both located in Cagliari. The reasons for such a choice derive from the fact that the former is the first and the largest Sardinian project, while the latter is certainly the most important and technically difficult as far as solving the problems of the connection and harmony with the pre-existent ancient structure is concerned.

SEMOLERIA ITALIANA-SEM (ITALIAN MILL)
Cagliari, 1904–5[11]

Coinciding with the late start of the modern age in Sardinia, the Cagliari future industrial area began to emerge near the port and the railway station;

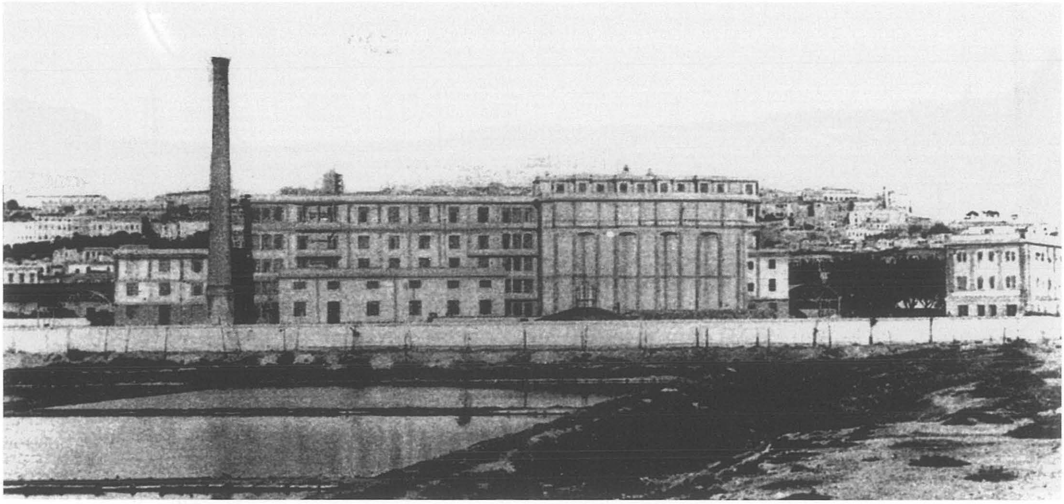

Figure 4b
Semoleria Italiana: the newly-completed mill, 1905. Archivio Storico del Comune di Cagliari, henceforth ASC

exploiting its privileged position as regards the transport system, it would see the rapid rise of the first industrial plants. The agricultural, and particularly cereal production, of southern Sardinia above all favours the grinding and transformation of grain. The SEM mill, inaugurated on the 21st February 1905, was, at that time, one of the biggest factories in the Kingdom, and the Company-Società Anonima Semoleria Italiana, the owner of similar structures in Liguria and Leghorn, was the biggest national milling industry.

The work in Cagliari constituted the first Sardinian project carried out by the Porcheddu Company and, considering its four-hectare extension, also the largest and the most complex; in fact, it also included silos for the preservation of corn, the grain press for milling and the storehouse for grain and flour. A power station, administrative offices and a small block of flats for workers are also provided. The heterogeneity of buildings, the important size of loads acting on the structures, the distance of the yard from headquarters, Porcheddu's need to establish relationships with suppliers and, finally, workers with no previous experience in building with reinforced concrete, all complicated the project. The innovative aspect, for the island, is also witnessed to by the fact that the yard in Viale La Plaja, with its daily 400 workers, soon aroused the interest of citizens too such an extent that the Prefect of Cagliari went in person to visit the buildings under construction to watch the casting of a floor in reinforced concrete, the first in the history of Cagliari.

The most evident characteristic of the SEM complex is that, even though it represented the beginning of the new constructive technique in Sardinia, it already benefited from Porcheddu's long experience, using the frame system in an absolutely modern way. Thus, it was possible to obtain large internal spaces for storage and working, lit by several skylights in the ceiling and see-through fronts with large windows, typically industrial and modern; traditional continuous masonry is still used only for lower buildings, in any case roofed with reinforced concrete.

All ceilings are of the Hennebique type, and all archives documents demonstrate that, for all inflected structures the principle is scrupulously applied according to which, in correspondence with fixed joints, iron bars are taken from the lower to the upper edge of the beam section, following moment inversion.

The main characteristic of the SEM complex is the ten vertical silos, almost 15 metres high: they are full masonry cylinders, bordered by hooping edgebeams

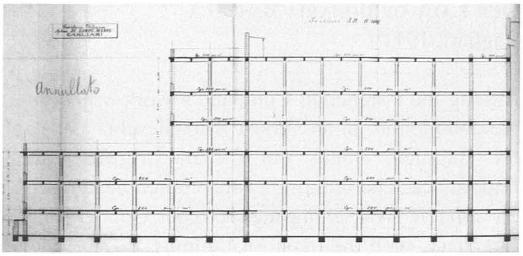

Figure 5a
Semoleria Italiana: a corn store vertical section, evidencing the pillar frame, Cagliari, 1904. (APT)

made of reinforced concrete. Silos are located in two lines, made up of five elements each connected by perimetrical bearing walls that, along with the flat covering floors and the trunk-conical ones of the lower hoppers, act as a further control on the whole system.

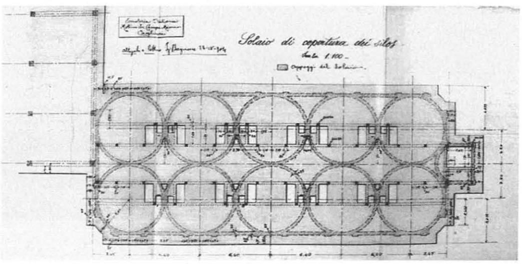

Figure 5b
Semoleria Italiana: a corn silo horizontal section, Cagliari, 1904. (APT)

As regards the internal composition of the reinforced concrete, we have no precise information, as in the archive files, all the strictly technical and descriptive data on the structures and rebars, destined for the yards has been lost. The only thing that can surely be affirmed is that the Hennebique system was rigorously applied, since from a packing list of the ironwork from Genoa, the shipping of bars and «metal strips» (the typical flat iron for the stirrups) emerges, and in a bill of iron quantities, we can find the difference between bars with a circular and «half-round» section, which we said was a personal

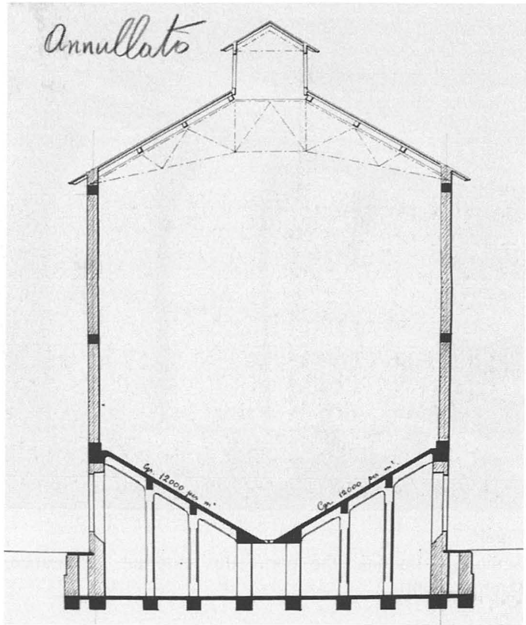

Figure 6
Semoleria Italiana: a corn silo vertical section, showing the reinforced concrete cross-ribbed hoopers and foundations, Cagliari, 1904. (APT)

Porcheddu patent for improving the adherence between iron and concrete. The floors are double framed with visible ribs, as was common for industrial premises. The foundations are also made of reinforced concrete, on plinths for the pillars and continuous along the outer walls. With the exception of two overhanging balconies on the mill building produced by prolonging the bearing beams of the floor beyond the facade, there are no projecting elements.

Given the purely industrial nature of the buildings, there is no space for decoration, although in one sense it is indirectly expressed by the crowning cornices on front which, together with the relief profiles of vertical structures, seem to follow in the wake of Perret's «structural classicism», resulting from the coupling of giant order pillars and overhanging «trabeations» of reinforced concrete. It is possible to find another very slight decorative element on the fronts of silos, necessary closed, whose structural niches are profiled by sinuous liberty scrolls that

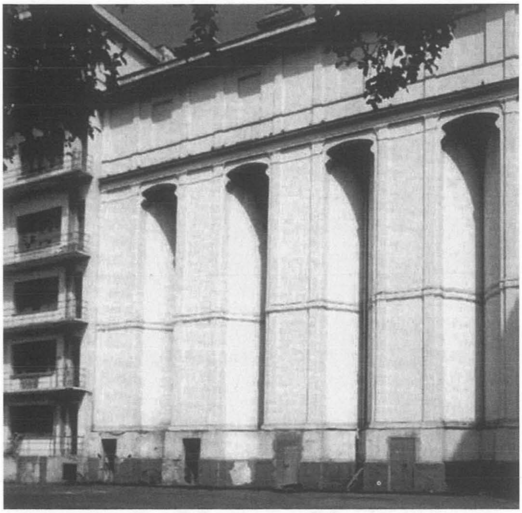

Figure 7
Semoleria Italiana: the corn silos external appearance, Cagliari, 1990

mitigate the exclusively functional aspect of grain silos.

The art-nouveau friezes blend with the agricultural nature of the work done in the factory. This is witnessed to by the decoration of the entrance, modestly framed by ears of corn and volutes in contrasting colours with the words «Semoleria Italiana» inscribed on the arch. This extremely complex structure was further enlarged only two years after the drawing up of the first plans, with the creation of additional warehouse construction of workers' lodgings. The SEM in Cagliari could be compared with the grain silos in the port of Genoa. Their complex plan, concerning all aspects of the project, from the arrangement of surrounding areas and shipment docks to details for grain-lifting equipment, was entirely conducted by the Hennebique headquarters in Brussels. In addition, the affinity between the two buildings is demonstrated, in addition to their similar use, though on a very reduced scale, by the fact that the SEM planner, engineer Carlo Bagnasco, was one of the managers of the Genoa branch of the Porcheddu Company, and he certainly supervised the building of the big silos.

Our Lady of Bonaria Basilica
Cagliari, 1911[12]

Among the Porcheddu Company's work in Sardinia, the completion, in an almost Brunelleschian way, of the Basilica, stands out for its originality and importance. The building of the church began on the 25th March 1704, alongside the older Gothic-Catalan sanctuary, with the intent of building « . . . el mejor templo, y mas capaz de todo el reyno» (Sulis 1935). However, from the beginning, the building history was a troubled one, so much so that in 1804, work was interrupted, leaving the high coupled columns and the outer walls at the mercy of the inclement weather. In 1866, with the expropriation of ecclesiastical property by the Italian State, the area of the new church became city property, and finally in 1910, thanks to the generosity of the citizens of Cagliari, funds for its completion were made available.

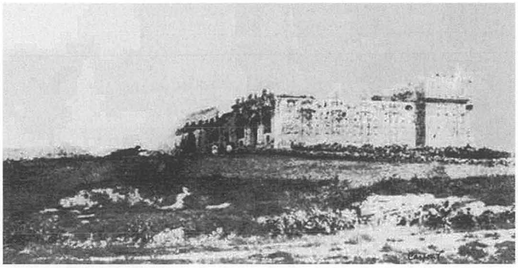

Figure 8a
Basilica di Bonaria: view of the unfinished church, Cagliari, 1854. (ASC)

Figure 8b
Basilica di Bonaria: view of the newly-completed church, Cagliari, 1926. (ASC)

In 1926 the Basilica was consecrated, but in 1943 a bomb fell inside and destroyed the stuccoes without damaging the structure. After the War, it was restored, giving it its present appearance, without restoring the caisson. The choice of not superimposing decorations on the plastered structures make the different nature of the limestone columns and the reinforced concrete vault explicit, highlighting the heterogeneous techniques, a mixture of tradition and innovation, that characterise the Basilica.

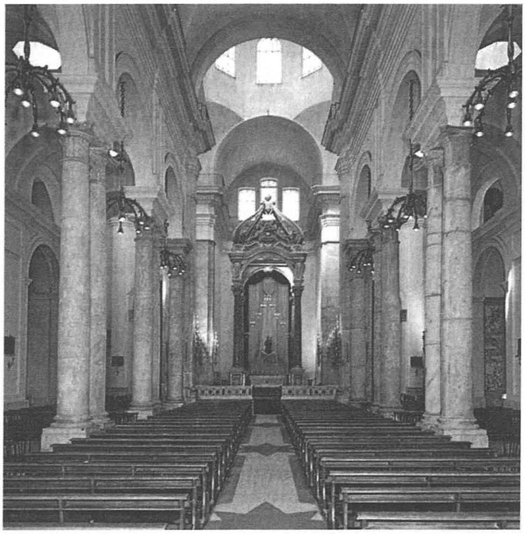

Figure 9
Basilica di Bonaria: church interior showing the twin columns in limestone blocks and the overhanging reinforced concrete slabs, Cagliari, 1990

The work carried out by the Porcheddu Company concerns roofing and the dome. Simonetti's role as planner as well as supervisor of the structures, was decisive in the choice of reinforced concrete rather than a traditional vault made of bricks. Starting in 1910, before roofing, it was necessary to consolidate the existing structures, reinforcing the foundations, the drum limestone columns the walls, not sufficiently stable.

Archive correspondence between Simonetti and Porcheddu meticulously lists all the parts to be built: the roof of the nave, the aisles, the transept, the

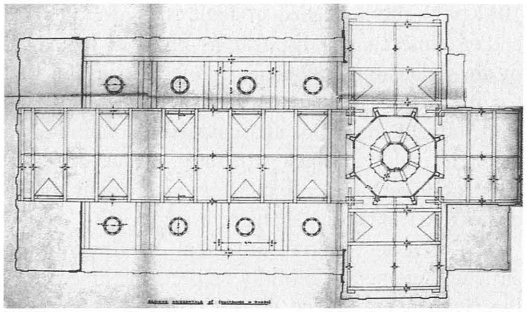

Figure 10
Basilica di Bonaria: plan of the church with the vaulted roof projection, Cagliari, 1911. (APT)

pronaos and the dome at the intersection of the nave and transept.

The principle applied was that of preparing a load-bearing skeleton directly supporting all the covering structures and masked at the intrados by thin barrel and cross shaped slabs of constant thickness, variable between 10 and 20 cm, which worked as a «period» false ceiling, imitating brick vault. Fortunately the availability of all the plans and the calculation note-book for all the church structures, dated 1 December

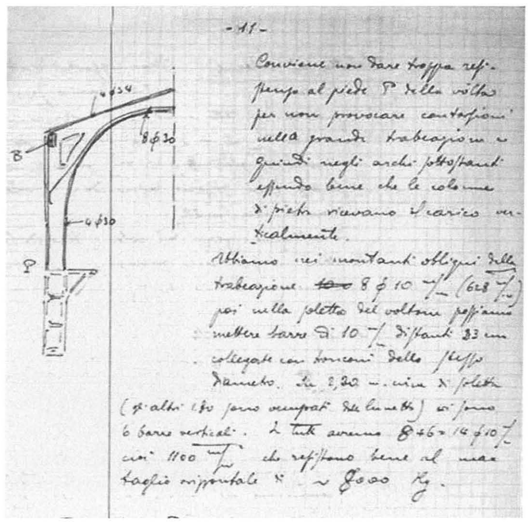

Figure 11
Basilica di Bonaria: part of the calculation notebook concerning the central nave roof, Cagliari, 1911. (APT)

1911, with the indication of static schemes, of stress and of reinforcement dispositions, precisely annotated by the calculating technician, provides a useful tool for the understanding of the technical aspects and static functioning of this unusual mixture of reinforced concrete and traditional structures, which presents, compared with other examples in Cagliari, some distinctive technological characteristics.

The placing of reinforcement in the varying structural elements faithfully respects the precepts of the Hennebique patent: stirrups are always present, and arches are reinforced according to the moments, with the inversion of irons 30° from the impost; thin slabs are reinforced by mesh that follows the sweep of vaults, as a continuum of the lunettes, with the exception of the dome which, being subject to extremely variable stress, is prudently reinforced symmetrically on its two faces. The central problem in this work arises from the discontinuance in structure, due to heterogeneous materials; thus if on the one hand it is necessary to produce a cohesive whole, on the other hand fixing have to be such that they can transmit only vertical loads to the stone columns and the wall. Along the nave, it was decided to put a sequence of large arches which marked the spans on the coupled columns and a massive trabeation almost two metres high which constitutes a strong stiffening element and distributes loads longitudinally; transversally, given the impossibility of guaranteeing a lack of horizontal components, an attempt was made to create a hinge at the base of the trabeation, to avoid the transmission of bending moments to the columns; the articulated joint was obtained by driving reinforced irons into the stone for almost 50 cm. In addition, the structure supporting the roof itself is made up of continuous hut-shaped elements (an 11–metres aperture), while the non-supporting slab of the vault, with the lunettes continuing, is created by a slightly reinforced thin lamina, which transmits very low thrust.

Along the transept, lacking the action of aisles, the walls are made higher, bending them to the height of the 30°-plane of the arch, to build only at this height

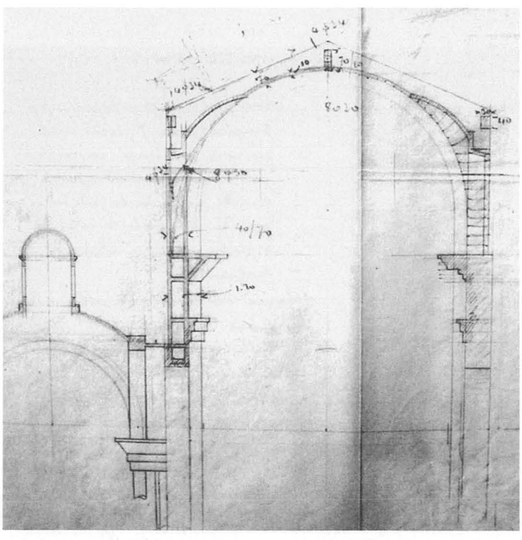

Figure 12
Basilica di Bonaria: central nave section bearing indications about reinforced concrete structure and iron bar diameters, Cagliari, 1911. (APT)

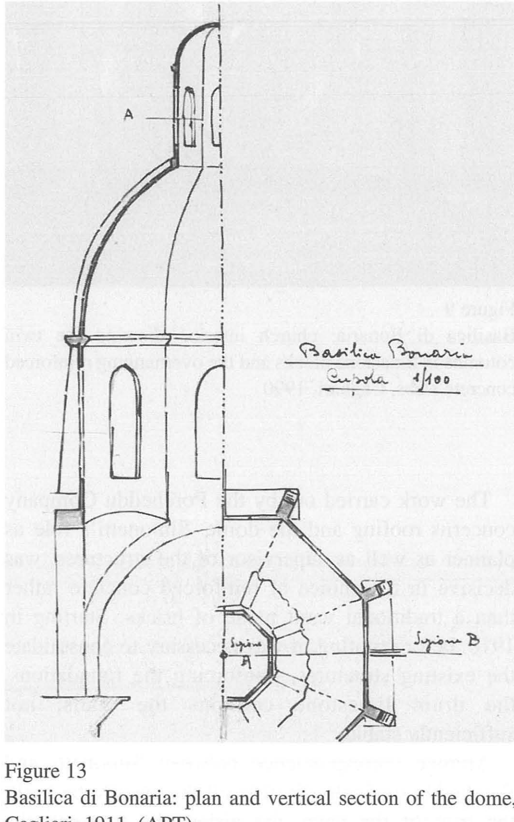

Figure 13
Basilica di Bonaria: plan and vertical section of the dome, Cagliari, 1911. (APT)

the polygonal structure of the roof, so that it is possible to have the joint at the point of minimum flexing moment. Moreover, the supporting section is reduced with respect to wall thickness and divided from it by the interposition of a paper sheet, so as to realise a sliding restraint, trying to completely annul the horizontal components and avoid overturning action on the masonry.

However, the pride of builders and citizens was the big dome, raised 50 metres above the floor and visible from every part of town. At the intersection of the Latin-cross plan, there are four vertical pillars which, joined by four spherical pendentives, support the octagonal drum from which the eight lightly ogival cones forming the dome, closed on the top by the lantern, branch off.

The shell that constitutes the dome is not simply a covering «skin», as it is in the naves, but with the help of stiffening ribs on the edges, is a supporting structure. The high shape is sufficient in itself, to render thrusts vertical; the combination of the two barrel vaults, the nave and the transept, which intersect orthogonally, is perfectly able to absorb all residual horizontal components, on condition that the system is firmly fixed to the piers, again driving the irons deeply into the masonry structures.

Although Porcheddu was new to extraordinary projects, the technical and building difficulties of Bonaria Basilica are also confirmed by the fact that himself recognised it as a rarity, asking Simonetti to take some photos of the yard during casting.

Within trends regarding the history of building techniques and the saving of twentieth century architecture, the research illustrated has allowed a precise analysis, though limited to Sardinia, of engineer G.A. Porcheddu's work, the functioning of his Company and the nature and structure of its archives. At the same time, the computational and construction methods of the first structures in reinforced concrete in Italy using the Hennebique method have been analyzed and reconstructed; we have demonstrated that such a method is the best suited for facing the test of time and the demise of the classic theory of elasticity.

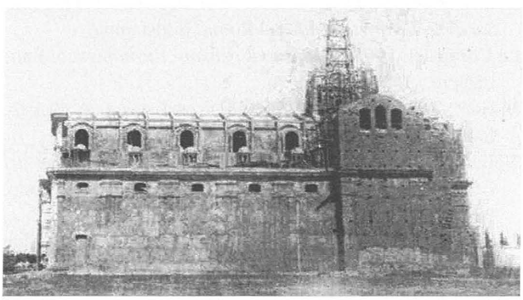

Figure 14a
Basilica di Bonaria: setting up the dome centre, Cagliari, 1911. (ASC)

Figure 14b
Porcheddu's advertisement in an old review, 1912

Last but not least, we have highlighted the construction of some complexes and buildings, not only those illustrated here, which have contributed to the urbanistic, architectural and economic history of the city of Cagliari.

NOTES

The present work is an abridgement of the still unpublished research project entitled «La Sardegna e l'innovazione architettonica alle soglie del Moderno. L'ing. G. A. Porcheddu e le prime realizzazioni in conglomerato cementizio armato», carried out by the author under the supervision of Prof. Antonello Sanna, at the Dipartimento di Architettura dell'Università di Cagliari and with the financial contribution of the Regione Autonoma della Sardegna.

1. «As constructions made of reinforced concrete, we mean those realised with concrete or beton (slow setting Portland concrete, with sand and gravel) reinforced by an iron skeleton or, better, mild steel, plunged in it. The jointed use of the two materials, concrete and iron, is

done in such a way that they react to the external strain, leaving the concrete the duty to resist the compression stresses and to the iron that of opposing the stretch stresses». (Mörsh [1910]1923).

2. « . . . [the reinforced concrete technique] is the finest and the most precise and also the cheapest: It combines the opposite properties of heterogeneous materials such as iron and concrete to resist at opposite tension (traction and compression) that are generated in the same structural elements» (Le Corbusier [1946] 1965).
3. We are referring to objects such as Lambot's boat (1848) and Monier's flower box (1849).
4. We are thinking about the first small floors with very short span patented by Monier, Lambot, Coignet in France and Hyatt in the United States.
5. For an accurate study of the many Italian and foreign patents and their specific characteristics see Iori (2001).
6. For a detailed study of Porcheddu's activity in mainland Italy, see Nelva and Signorelli (1990).
7. On the social and economic environment in Sardinia during the first years of the XX century, see Berlinguer and Mattone (1998).
8. The list of the works realised by the Porcheddu Company in Sardinia: 1904–Milling complex of the Semoleria Italiana, Cagliari; 1905–Enlargement of the Semoleria Italiana, Cagliari; 1905–Workers' lodgings in the Semoleria Italiana, Cagliari; 1905–Floors in Picchi house, Cagliari; 1906–Town Hall, Cagliari; 1906–New Picchi House, Cagliari; 1908–Floors in the School and Town Hall, Meana Sardo, (CA); 1909–Floors in the Workers' Society building, Cagliari; 1910–Salesian Fathers' Oratory, Cagliari; 1910–Enlargement of the Liguori factory, Cagliari; 1910–Water cistern in S. Vero Milis (OR); 1911–Floors in Costa house, Cagliari; 1911–Severino pasta factory, Cagliari; 1911–Basilica of Bonaria, Cagliari; 1911–Floors in Balletto mansion, Cagliari; 1912–Choir stalls of S. Lucia Church, Cagliari; 1912–Floors in Severino house, Cagliari; 1912–Floors in Liguori house, Cagliari; 1912–Water cistern in Dolianova (CA); 1912–Bridge on Mannu brook in Portixeddu, Buggerru (CA); 1913/14–Balletto pasta factory, Cagliari; 1913/14–Building of the Banca Commerciale Italiana, Cagliari; 1914–New floors in Balletto pasta factory, Cagliari; 1914–Flat terrace floors in Balletto pasta factory, Cagliari; 1914–Presbytery floor in S.Eulalia Church, Cagliari; 1929/30–Bridge on Pedrosu brook, Bonorva (SS); 1929/30–Retaining wall and floors MVSN barracks, Bonorva (SS).
9. Short historical notes are available in the Archivio dell'Ordine degli ingegneri della provincia di Cagliari.
10. For a detailed description of the archive and of its contents, see Nelva and Signorelli (1990, 25)
11. Original denomination: mill near «Su Campu Mannu»; location: viale La Plaja, Cagliari; destination: milling factory; client: Società Anonima Semoleria Italiana, Genoa; planner: engineer Carlo Bagnasco of Genoa; building firm: Colombo-Ventini-Martino & C. Milan and Genoa.
12. Original denomination: O. L. of Bonaria; location: Viale Bonaria-Via Milano, Cagliari; client: Padri Mercedari; planner and work director: engineer Riccardo Simonetti; responsible for the structures: engineer G. A. Porcheddu and engineer Riccardo Simonetti.

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The wall and the frame: Design and technology. Between autarchy and reconstruction in Sardinia

Antonello Sanna

It is common opinion that the presumed unity of the Modern Movement in architecture is made up by an extremely plural and articulate reality of local movements. Sardinia as a case study can contribute to show the non-linear way of the relation between technology and project, starting with technology's peripheral and central areas. Already at a first survey, some evident paradoxes are pointed out: among these we find the first undeniable fact that the first affirmation of the new reinforced concrete technologies is relatively precocious and mature, even if in a low technical contents context.

If the iron technologies have reached Sardinia with late '800 stations and markets, in the beginning of the new century a new experimental sector that will represent one of the most expressive paradigms of modernity shows up: the RC frame, with the progressive emerging of its plot to the building surface.

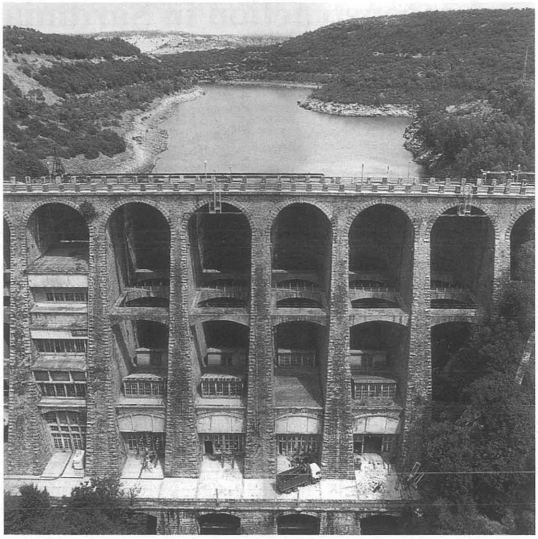
In 1904–1905 Giovanni Antonio Porcheddu, Sardinian engineer graduated at the Polytechnic of Turin, after becoming rapidly the leader of Italian agents of the Hennebique patent, starts for the grain Ligurian industrials the building of the silos in the town of Cagliari, just a few years after he had built the ones in the port of Genoa (Nelva and Signorelli 1990).

The order is referred to special structures like silos and warehouses, designed with a multilevel structure with a ca. 6,5–5 m mesh, calculated after the empirical simplification of the Hennebique method. For many aspects misleading, but undoubtedly effective, it supposed that the tensions are evenly distributed in the concrete and equally shared with the iron.

The Semoleria Italiana plant is retained in Sardinia a milestone of the «engineer way» of modern architecture which will proceed on parallel never meeting tracks, full in reality of influences and contamination with other leading experiences of the Modern Movement.

Another important buyer of the Porcheddu reinforced concrete, the Banca Commerciale, was in those years busy in advertising and financially sustaining the electrification and the land reclamation. At the same time the project for the dam on the Tirso was being completed. At the end of the First World War in 1920 the final project was launched in which Luigi Kambo, engineer, transformed the work into a multiple arches dam built with local granite and trachyte stone, joined with conglomerate vaults. The great S. Chiara dam (Bitti 1998) represents a grand main point of modern *constructivity.* With the energy of its structures it shows one of the most credible versions of the engineering functionalism, particularly versatile and diligent in marrying the use of local materials to calculation and structural conception.

These great works live together with a technical and enterprise local net, which starting with a deliberate distance to external contributions, will hardly learn to be confronted to new technologies.



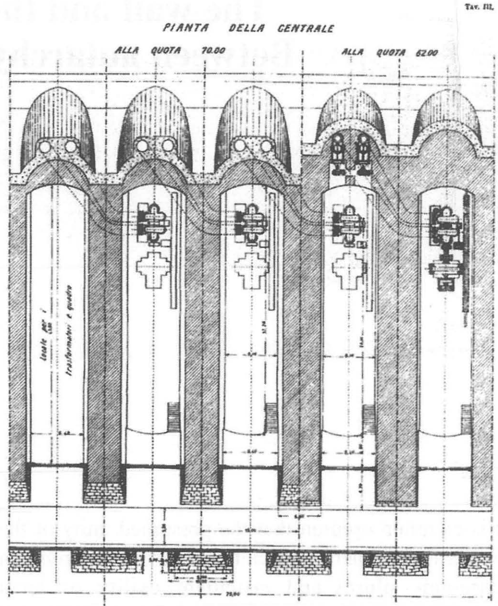


Figure 1 and figure 2
Multiple arch dam of santa chiara, seventeen 15m. Spans, connected with RC vaults. The buttresses are armed with iron bars

This exchange will generate results and realisations able to communicate with Italian and international design cultures.

In the following two decades this will probably be in Sardinia the main interpretation of the relation between project and construction: the dialectic between the absolutely pervasive wall culture and the progressive affirmation of the new RC frame technology, in fields and typologies of growing importance. The diffusion of technical instruments, the more refined simulation of structural behaviours of the new materials, the capillary circulation between enterprises and professionals of technological knowledge mark a slow but non-stopping decline of both patents and specialised firms. The great process starts which only the Reconstruction in the second post war will conclude: the substantial replacement of the wall with the frame in the most diffused building site and enterprise practices. It is not by chance that among many polemics in 1925 and following years the issuing of an official law for the calculation of reinforced concrete erases a great part of the patents of the new material; a few years later in 1933 the Società Porcheddu is winded up (Iori 2001).

In the ocean of conventional building a steady red thread joins the great scale infrastructures experience with the following one of reinforced concrete in urban buildings, especially in the town of Cagliari. It concerns the association of traditional wall shells and RC structures: among these last ones, the floors seem to be already diffused in the '20s, while just starting in the '30s the exposed beams show up, and the pillar are almost always hidden in the wall. Some interventions made by the Società Anonima Italiana Ferrobeton are in this sense emblematic. Leader of the public orders in the period between the two Wars[1] Ferrobeton weaves a strong alliance with some of the local technicians, first of all with Flavio Scano, owner (together with his colleagues engineers Binaghi, Pacca, Fadda and Tonini) of the first professional bureau able to control the RC technology. Due to this alliance are some of the very first private and public buildings starting in town between the two Wars the new season of reinforced concrete. In 1929 the Caserma dei Regi Carabinieri is designed with a

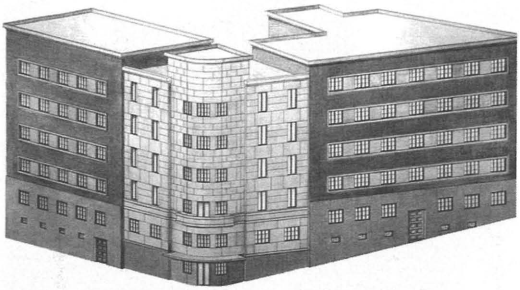


Figure 3
Corner building by eng. Fadda and Tonini, Cagliari 1937

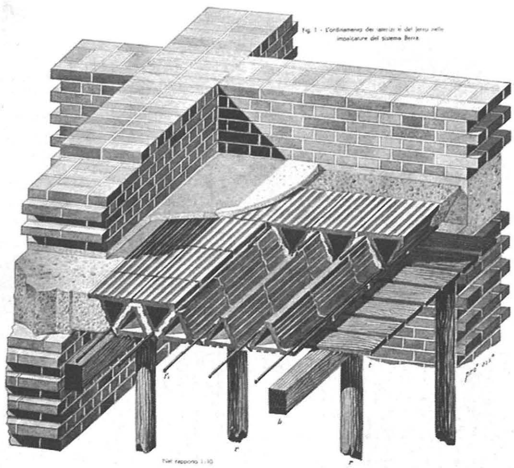


Figure 4
Berra floor built with triangular sectioned hollow blocks

massive wall shell decorated with refined concrete stone finishes. The facing, scanned with classicist pilasters, declares in the monumental corner solution with four columns the hidden pillar which is revealed mostly in the great Hennebique double beams plot.

In the choice of the most updated European references the solid plastic *constructivity* of Behrens in Vienna is taken as model. It is proved by a corner solution designed in the late '30s by the engineers Fadda and Tonini, designers that expanded their action radius to the management field. The two engineers already having, ten years after, a prime role in the reconstruction of Cagliari in the second post War, perfection the «mixed» structural scheme, with RC hidden in bearing walls, and used as a prime material just in the execution of floors (Loddo 1999).

It is symptomatic that in this private building we find the same type of concrete reinforced hollow blocks floor Berra, with triangular sectioned hollow blocks , that were already used in public works such as the Albergo del Povero in 1934 (Sanjust 2001) recently revealed by a restoration run on the 1935 primary school by Arturo Miraglia in Fertilia (the last new town in Sardinia).

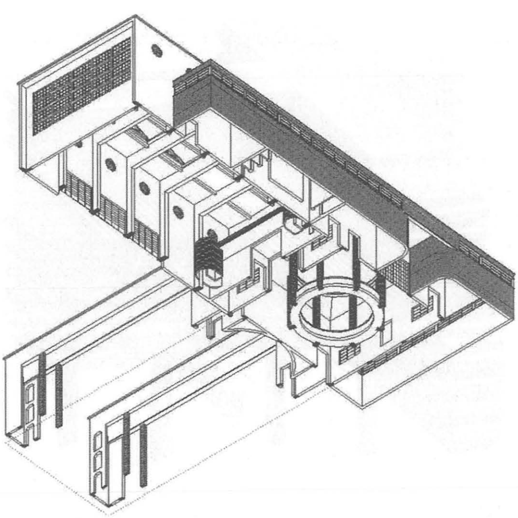
The vicissitude of the fascist new towns introduce in the regional architectural panorama further stimulations to develop project and construction towards modern experimentation. In 1935 appears in Mussolinia a new building complex thought to be the civic town centre. The Casa del Fascio with annexed tower of the lictor, and more, a gym school for the Opera Nazionale Balilla appear still today as a prototype of the lightness of European modernism, reinterpreted in an Italian/Mediterranean way.

In particular the gym is basically designed as a RC skeleton with a sequence of great portals. The relation to the wall shell is solved by the author, Giovanni Battista Ceas, with offset layers: the burnt brick striped façade marks the front, visibly advancing as to the frame wall (Pellegrini 2000, Sanjust and Santoni 2001).

Turning again on the side the brick wall leads toward an open swimming pool, framed by two portals more than 20 m wide which condense many of the experimental contents of the building. They are built with RC and have a U section, with the hollow on the lower side: the extreme thinness of the section is contrasted by the resistance given by the form and by a calculation hypothesis that foresees the execution of a simple support at the extremity, with sliding trolleys, of which the designer gives the executive project.

Not all secondary tensions though have been adequately calculated as an extremely thin intermediate cement pillar (coated with burnt bricks) shows by now heavy damages (Sanjust and Santoni 2001).

The work-line proposed by Ceas was not leaking in influences, and exactly on the topic of the relation



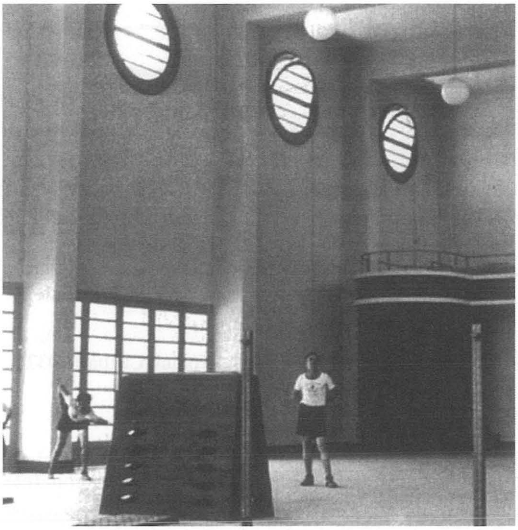


Figure 5 and figure 6
The gym in arborea by G. B. Ceas, 1935. The axonometric projection from below and a picture of that time show the system of frames defining the volume

between wall and frame: the gym is in fact a paradigm of how the potentials of both can be used in an appropriate and «modern» manner. The author applies frame works in the design of more aerial and exceptional spaces, and appoints to the wall (not in vernacular tradition) the task of communicating with the Mediterranean light and climate. This building marks the value and together the limit of the early '30s experimentation: great space to innovation, in the best case, but also weak incidence and penetration on the technical and enterprise field.

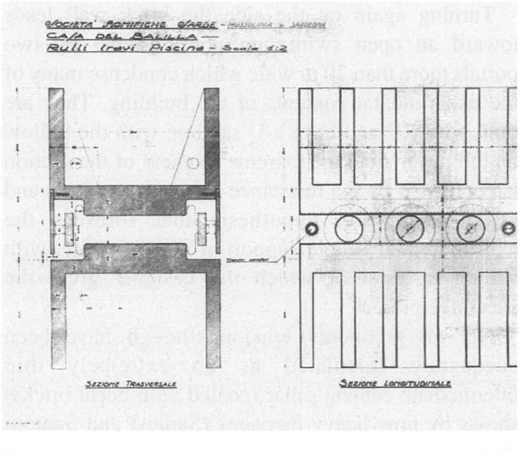


Figure 7
Detail of the technological solution for the beam simple supports of the gym: The sliding trolleys

Furthermore, as known the international sanctions which paralyse or re-dimension high tech products importation, mark after 1936 the division between the expansive phase and the autarchic retreat. The new autarchic architecture will consequently avoid an integral use of RC with the employment and the reinterpretation of local stone walls and reserving iron and concrete especially to horizontal elements.

Due to one of the paradoxes that after all represent a constant in Modernity, some of the most original contributes are produced in this phase on the topic tradition/innovation, local materials/modern languages.

In Sardinia this experience will be put into realisation in an accomplished way first in Carbonia, starting in 1938, and right afterwards in Cortoghiana in 1940–42.

The initials of the same enterprises that use to dominate the building market in the late '20s recur in the building contracts for the two new coal towns.

Ferrobeton for instance will construct buildings designed by Eugenio Montuori, as well as the enterprise belonging to the engineers Fadda and Tonini (who just terminated the corner building in via Pola-Cagliari); both are to be found again ten years later in the building contracts for the INA Casa in Cagliari, representing the first building enterprise of the Reconstruction.

Carbonia, giant contextual and accelerated building site of many thousands of lodgings is the real experimental field of the low cost mass building that will be realised in Italy just after the Second War.

The autarchic presuppositions are well present imposing heavy restrictions during the works:

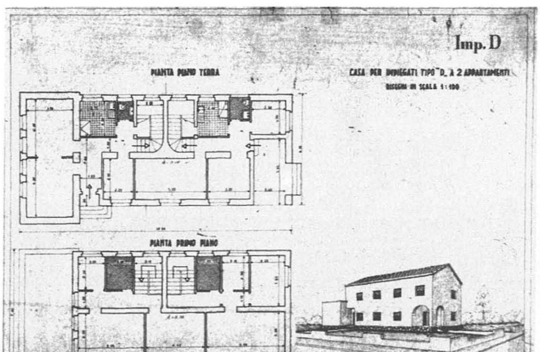
«many adjustments are to be noticed . . . suggested and imposed by the difficulty of finding the necessary building materials to carry out the works as designed and contracted[2]».

The contracts for public buildings do not foresee the use of a bearing RC structure, which application is hasty limited to «parallel or cross ribbing slabs with special or hollow blocks[3]».

Very much detailed descriptions are reserved to walls, especially to face walls. The result is a «minimalist» building panorama, assuming great interest and suggestion where, once again, a non-vernacular use of the wall is achieved.

Some of the most successful residential types, among which are Montuori's, Lenti's and Di Tomassi's houses, are based on the combination of the pure prism of the building and the trachyte block walls crossing it in the only possible way: with the external staircases.

Cortoghiana is founded as a more circumscribed urban entity, with a very rational and rigorous design invention. Saverio Muratori catches in this case one of the most important aims of the Modern Movement for which «less is more». He works following typological and morphological rules, with very much calibrated exceptions: an exact and strict grid that ladders in the centre to host the Piazza Venezia; a few building types: one is represented by the line houses with arcade following the great central square, the second by the little two-family two-storey houses defining Cortoghiana's margin to the countryside. The same coherence avoids any vernacular implication in the use of local stone, in the traditional striped and plastered wall, in the pitch roofs.[4] An autarchic answer is to be found, except in those typologies deliberately lacking overhangs, also in the arcades where the trachyte stone abutment and its 3 m width (the dimension, referred to a height of 5 m gets close to the rule of three) allow a maximum economy on the RC architrave carcass. Moreover it becomes the formal language of the metaphysical Piazza Venezia, realising a paradoxical and obsessive iteration which transforms the arcade from a classical motif to a metaphor of modernity.



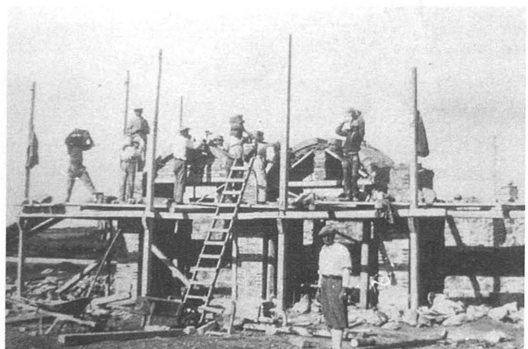


Figure 8, 9
The maximum economy on iron not only eliminates overhangs and reproposes exposed stone, but puts vaults into work again, replacing rc floors

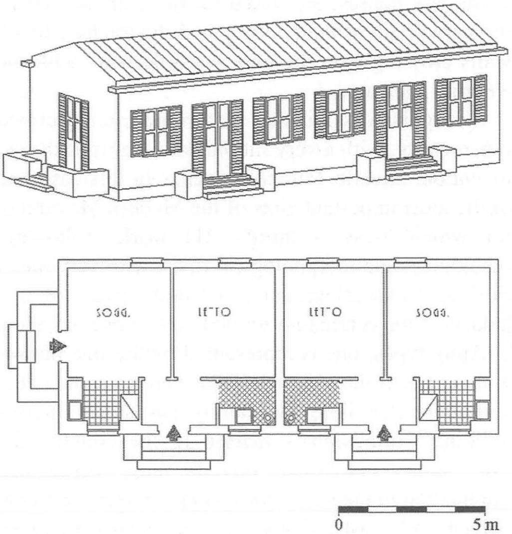


Figure 10
Minimal houses of the autarchic construction

Also in this case, the great lesson given by «autarchic Modern» consists in sublimating the expressiveness of the local material and wall construction, of the traditional building procedures, through a very dry design.

The passage signed by the War does not act in a decisive way on techniques, but changes the background scenario, focusing on the quantity and quality of the building production. The expansion politics of the «new towns» enter a quick and irreversible crisis, while the development of urban peripheries gets re-launched to incredible rhythms, also promoted with a public intervention for popular and mass lodging.

Building assumes at this point a precise anti-cyclic role, and gets the task to work as a flywheel for the labour (assuring at the same time the re-conversion of rural work into the most recent industrial processes). It is also therefore functional that it stays in an intermediate status between the craftsmen building-site and the most advanced industry. During the post War Reconstruction phase the same enterprises which in the '30s had experimented the passage to autarchy (in the meantime they had also achieved mass methods and techniques) use more and more frequently «new» RC frame technologies, from which each character of exception is now removed in order to be reinserted among the current building practices. Once again a decisive technical, cultural and

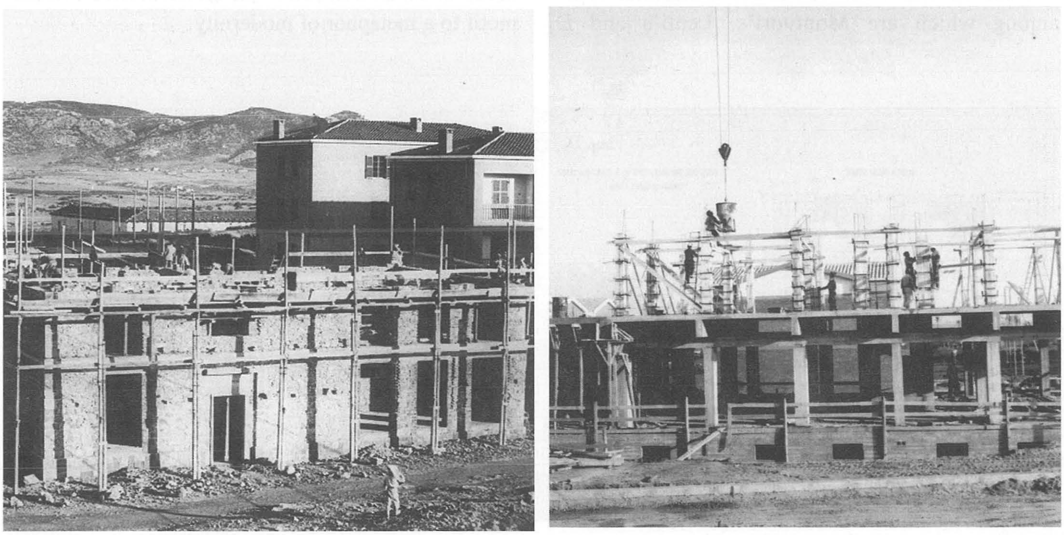


Figure 11, 12
Two building sites of the reconstruction. Right after the war the constructions in cortoghiana are planned and built after the «wall tradition» methods; ten years later in Cagliari the construction is reconverted to rc technologies

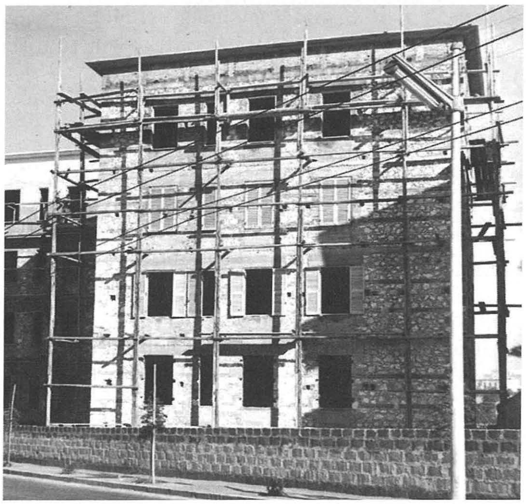


Figure 13, 14, 15
Apartment buildings in the garden-suburb planned by Adalberto Libera in Cagliari (early '50s). The author's perspective designs an extremely pure and rational volume, while the picture of one of the buildings under construction shows the prevalence of traditional technology and the realization alters some characters of the project

organisational passage is carried out by the designers of the roman school, called to direct the great building-sites of the INA-Casa programs.

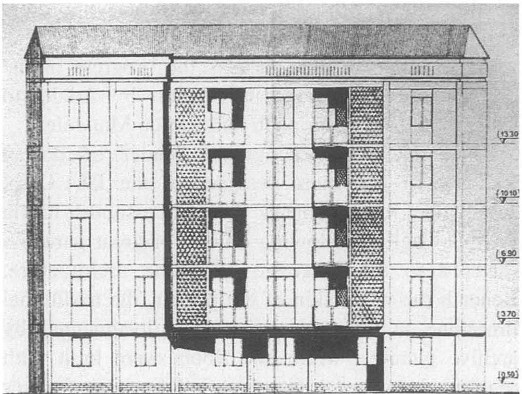
An example in this sense is the progress of the designs and realisations in Cagliari by Adalberto Libera, Maurizio Sacripanti and Enrico Mandolesi.

Since 1950 the recognised leader of Italian Rationalism and main designer of the INA-Casa, Adalberto Libera, projects the garden-suburb in via Pessina-Cagliari following criteria of great pureness referred to the language of frame architecture. Beneath the white skin of the plaster, the traditional limestone masonry shows up, as documented by archive pictures, while just floors were built with reinforced concrete. The first building site images showing a RC frame are dated in the mid '50s and are referred to the intervention of the INA-Casa in the north of Cagliari: a whole quarter, Is Mirrionis-San Michele is built with the new building system, and more it is the first case in which the social building is occupying an entire portion of town, influencing the enterprises in the following decades. The two complexes, built almost at the same time, well expresses some of the different possible declinations of the rational post-War language: opposite to Libera's clear plastic setting of the compact volumes is Maurizio Sacripanti's decided will to work on the tectonic «showing the frame» (also after Ridolfi's and Quaroni's contemporary experiences). Sacripanti will start a true battle run on telegrams and letters to induce the enterprise to build the exposed frame with the complicated profiles as foreseen by the project to express the different tectonic role played by supports and beams (Sanna 2002).

On the other hand Sacripanti will also design for his «towers» a local stone facing basement.

At the end of the '50 the younger Enrico Mandolesi, founder of a new school of design at the University of Cagliari, in the project at La Palma sets himself free from any local reference and transfers without regret Ridolfi's style with face frame and brick infill.

The two building site types (stone and RC) bring us back to the role played by the residential building in the Post War period in reconverting traditional crafts into new technologies. In very few years a whole organisational and productive universe gets upset and reshaped in function of mass building. It is in those years, for example, that the local building industry gets reorganised to produce the new burnt bricks



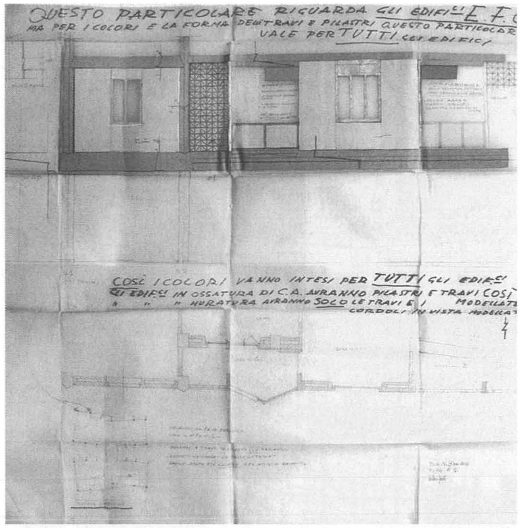


Figure 16, 17, 18
The «butterfly» building by M. Sacripanti in Cagliari (1952–'53); the draft of the executive solution shows the importance given by the designer to the realisation of the exposed frame detail

necessary to the renovation of the building system. The major furnaces (equipped since the beginning of the century with Hoffmann ovens) grow bigger, open new factories, get ready to improve the production 4–5 times especially concerning hollow bricks and floor blocks for beam and block floors.[5]

In Sardinia, the dialectic tradition/innovation, maybe more than elsewhere, hinges on the weave between handcraft and industry, local- and import materials, new and old crafts, urban and rural dimension. Therefore in an area that apparently seems not having experienced in front line modernisation, some of the essential premises of the architectural debate are embodied sometimes in an exemplary manner.

Notes

1. The show up in Sardinia of the Ferrobeton coincides with the decline of both Banca Commerciale and Gruppo Elettrico joined to it, and with the affirmation of the Credito Italiano (to which the Ferrobeton is joined) that takes progressively its place (Di Felice 2000).
2. *Relazione al conto finale del Lotto 23–23/35*, IACP Archive, Ufficio di Carbonia. In a similar document, referred to the Lotto 28–28/35 an «hyper-autarchic» variant is described: «the eaves' frame expected to be realised in RC was then modified and made out of bricks as imposed by the rules given by the Ministery for Public Works on the minimum reduction of metallic material» (Sanna 2001–2).
3. *Capitolato Speciale d'Appalto* of building types *A, K* and *Di Tomassi*, both attributed to Montuori (Sanna 2001–2).
4. It is a true «war building», that has to be built without


Figure 19, 20
The new social housing by Enrico Mandolesi in Cagliari-La Palma (1957–'58)

iron: a letter by Provveditorato alle Opere pubbliche dated 17 april 1940 states that of 300 q iron materials just 30 were allowed by the Ministery!» (Sanna 2001, 123).

5. In this way in the hinterland of Cagliari some new production plants are installed as Scanu in Assemini and Picci in Quartu, bound to mark in the following decades the universe of building base-materials (Sanna 2002–1, 152).

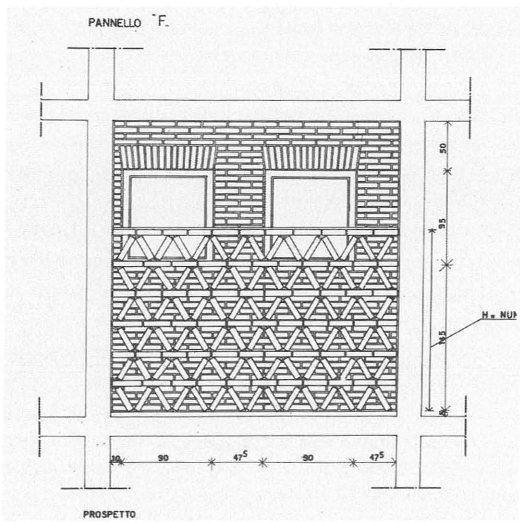


Figure 21
Exposed brick panels fill the spaces of the grid of the RC frame. Enrico Mandolesi, Cagliari-La Palma

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«Ponte vecchio» bridge in Bassano: An historical «excursus»

Carla Alberta Scapin

The bridge of Bassano is a work offered to the citizens, the visitors, and the students of the matter, as an example of historical and architectural permanence; a manufacture which was first built as a simple crossing and that has became through the years the real symbol of the city.

The bridge becomes a monument and is delivered up as an element of great importance for the city

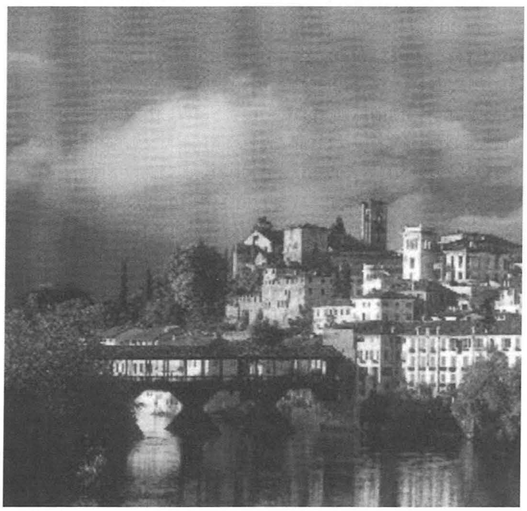

Figure 1
Il Ponte di Bassano (The bridge of Bassano). Cesare Girolimetto (1995). South view from Angarano. (Archives Cesare Girolimetto)

configuration; as a voluntary or obliged point of pause, as a clot for inhabited buildings, business activities and handicraft. It is offered like a support to the multiple sides of the city, able to create a place, a vital space, loaded with means, functions and historical deferments.

The departure point is the locality in which the wooden manufacture is laboured: Bassano del Grappa; Bassano is certainly one of the most singular Venetian citizens that has risen along the borderline between the plain and the hill. The bridge thus becomes the artefact needed to combine two natural separate places; a crossing that contains in itself the implications of a separation. Bassano means Brenta, Channel of Brenta and Valsugana. It is in this axis that the history of Bassano has always run, along with the history of its wooden bridge, as testified by a wide list of images and documents that reconstruct its shape since the Medieval Age. The new connection can be without any doubt considered as an important sign of environmental modification produced by human beings.

From the 1200's and through the centuries the bridge has always remained respectful towards the tradition: several generations of carpenters, builders, designers have perpetuated its original shape, which has always been considered by the local population as a sort of *limes*.

The structure during its 700 years of life has suffered from recurrent destructions caused by the terrible and sudden floods of the river, but every time

it has been rebuilt with the same features and materials which have always been considered the only ones suitable for its peculiar position.

The city has always had a tormented relationship with its river, as it often happens on a geographic and climatic border, where the water course frees itself from the deep valley which leads to the Nordic world of mounts and forests, transforming itself from a torrent into a river and facing this way the free adventure in a cultivated and urbanized Venetian campaign.

The conception of the bridge as inseparable from the urban plan of the city, planned as a hinge and a focal point from which the image of the city appears through its original relationship with the natural atmosphere and especially with the river. The fluvial landscape of the Brenta, that lengthens throughout alpine spurs and the low plain and rests on a weak layer, is conceived as a moment of fragile and sensitive equilibrium between hydrogeological system and anthropic landscape.[1]

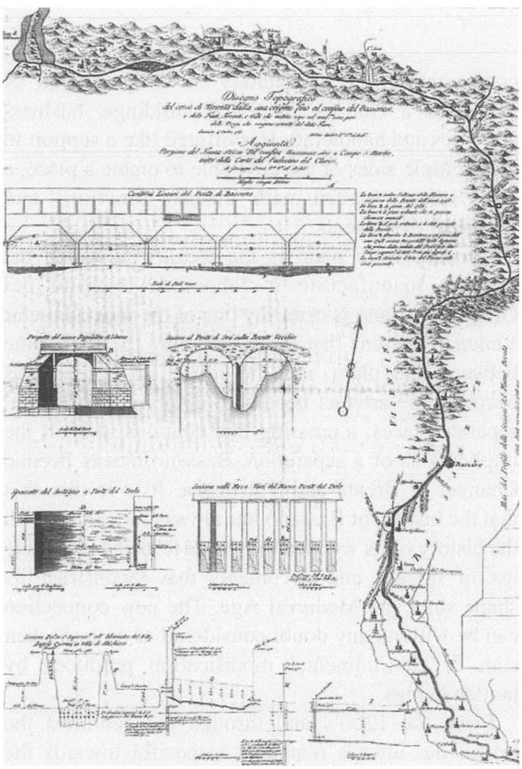

Figure 2
Rilievo topografico del Brenta (Topographical relief of Brenta). Antonio Gaidon e Guiseppe Ceroni (1788). Brenta is raffigured from the mountain section to the Venetian lowland and the territory of Padova. There are also represented the ordinary levels of 1748 and 1785 floods. (Archives Civic Museum Library of Bassano del Grappa)

The morphologic model of the Brenta's alluvial system is divided in three parts because of the various geologic components which have contributed to its formation; the central part from Bassano to Piazzola is characterized by several water courses which interlace themselves forming the typical islands of the *interlaced channels* morphology; a typical feature that produces a continuous transformation of the fluvial appearance.[2] The strong slope of the water course after the section of the mounts is the cause of a continuous transport of rough material, gravels, pebbles and sands: one of the main reasons of the degradation of the structure of the wood of the bridge. In fact, the first norms that guaranteed the respect of the manufacture came from the old city Statutes of 1259 and 1295, which protected it thanks to a detailed system of rules: the duties. Nevertheless the receipts brought to the municipal cashes by the transport of goods and the human passage were not always enough to cover the expenses for the simple maintenance of the lumber.

Some new kind of protection towards the fluvial atmosphere were adopted just after the quick expansion of the Venetian possessions, with the constitution of a new organization: the State of Mainland, in contrast with the State of Sea.[3]

The bridge in the centuries

The more reliable document testifying the existence of the bridge in Bassano is the written of Geraldo Maurisio, who in its *Cronica* describes the meeting, happened in 1204, between Ezzelino III, coming from Brescia, and its servants, in «platea, quae est a capite Pontis Baxianis» (*Maurisio*,1726). This place seems to be the ancestor of the present structure, a fact which is also proven by the loan contracted by the city of Bassano in 1222 «for laborerio pontis Brentae». The bridge then is mentioned in the Papal bulls of 20th and 21st October 1227, which guaranteed the protection of the Pope to the minors of the convent «ecclesiam Sancti Donati de Angarano sitam

in capitae pontis de Baxiano» (*Verci*, 1779), and fixed the mutual positions of the church of Saint Donato and the bridge, which was probably sited to the North if compared with the present position, in the slope of the river turned to the city.

From then, with regular expirations, the archive papers have recorded numerous participations carried out in order to restore or to rebuild ex novo the construction, which was repeatedly threatened by different menaces: the frightful floods, called *brentane*, the continuous usury of *stilate*. Against which the numerous rafts, which journeyed *in menada* along the course of the Brenta directed to Venice, violently hit, and man's steals of lumber from the bridge, built, like today, with wood of bay oak, larch and chestnut tree.

In 1524, an important innovation marks the history of the bridge, as it turns out from the Official Records of the city Council Proceedings, which deliberated a reconstruction of the bridge with stone and tile. The issue of the manufacture in stone still remains incomplete and lacking of existing documents do not allow a certain reconstruction of it; the only certainty is the destruction of the bridge caused by the *brentana* of 3rd October 1526. As a result of the short and ill-fated life of the bridge in stone, in 1531, Bassano finds again its bridge «riedificetur ligneus prout antiquis erat» constructed «in loco solito e iuxta solitum» (*Official Records of the city Council*, 1528–1536, 4/13), which, because of the continuous restorations, had a little bit changed its aspect from the original. There was certainly the introduction of three new supports but the bridge was always built in wood.

The 30th October 1567 the bridge of Bassano was swept up and destroyed by another violent flood of the Brenta. The first plan for a new bridge presented to the city Council 29th January and planned by an engineer of Cividale, presented a wooden structure with a mobile floor system, supported by four *stili*, able to unhook themselves in case of flood.

The innovation was not well received by the citizens, who appealed again to a consolidated tradition, and 28th February reached the deliberation of the Venetian Senate favourable for a reconstruction of the bridge with the previous materials and shape, thanks to the contribution of a famous architect from Vicenza.

Among the surviving documents, the name of Palladio appears for the first time in three distinguished

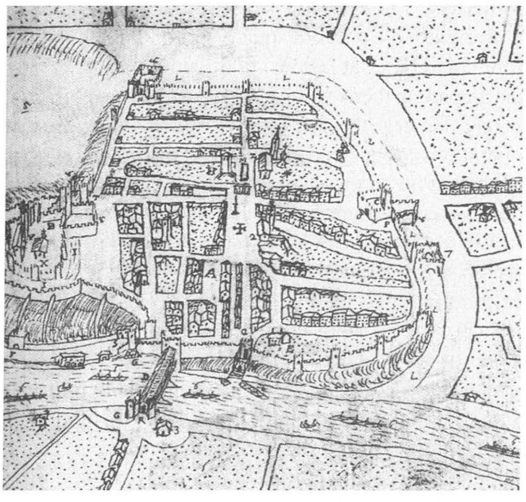

Figure 3
*I*dea di Bassano ampliato da Giangaleazzo Visconti nel 1388 (An idea of Bassano enlarged by Giangaleazzo Visconti in 1388). Francesco Chiuppani (1730). In the representation the covered bridge is put among the fortified entries of the city; it rests on two *stilate*. (Historia Bassanese, part two)

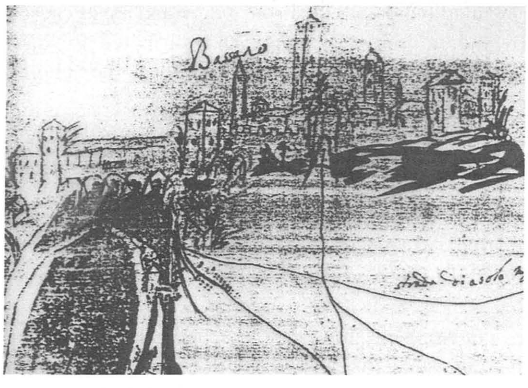

Figure 4
Mappa di Bassano e dintorni (Map of Bassano and its environs). Anonimo (1557). One of the first imagine of the bridge included in the representation of Bassano; it is flanked by towers and sustained by five *stilate* and can be considered the manufacture before the Palladian accession. (Bollettino Cisa n° 16 1974)

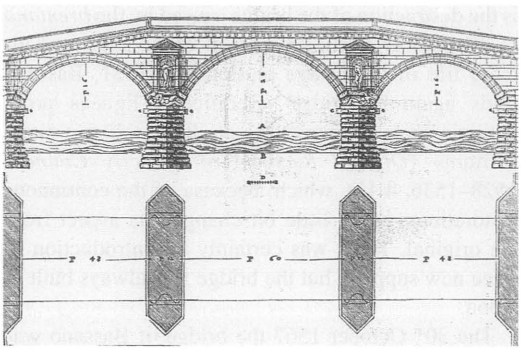

Figure 5
Invenzione di ponte in pietra a tre arcate (Invention of a stone bridge with three arches) . Andrea Palladio (1570). In criticism's opinion it is probably the model of the bridge that Palladio designed for Bassano. (Quattro Libri, Book III, pag. 29)

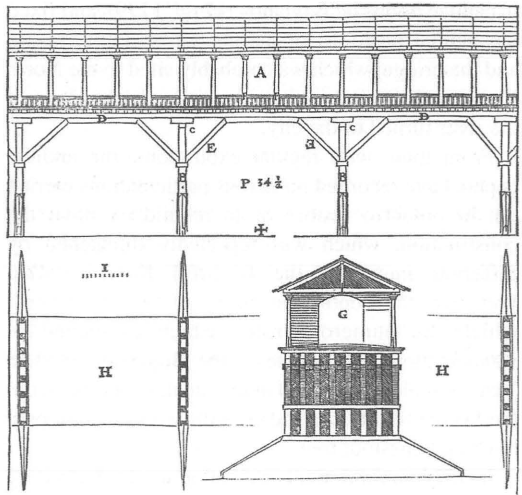

Figure 6
Ponte di legno a Bassano del Grappa (The wooden bridge in Bassano del Grappa). Andrea Palladio (1570). The bridge that is actually constructed and is named in Palladio's treatise. (Quattro Libri, Book III, pag. 20)

payment notes. The fist one dates back to 26th October 1596; maybe when Palladio's inspection happened. These payments represent a reliable source and confirm the existence of two plans: a balance refers to the first plan of bridge that Palladio had supplied, his indipendent *inventione* in stone, that was obviously discarded pro a wooden reconstruction.[4]

Palladio did not hide his irritation and anger caused by the refusal of his plan and attributed to «essi gentiluomini» the responsibility of the choice (*Palladio*, 1575, Third Book).

Palladio's words document that the architect did not want, in this particular commission, to produce an original creation, but to create a solid and very conceived work. Faithful to dictates deduced from the method of the *Antichi*, Palladio, respecting the previous tradition, introduced in the classic order balustrades and capitals supporting the cover.

The wooden structure ordered by Palladio rested on four articulated pylons, but in comparison with the present table in «Four Books Of Architecture», it is possible to discover some variations probably adopted during the phase of construction, or a little after.

At first, it seems already possible to glimpse, in the centre of the profile, an interruption of the balustrade, that can be compared to the present central balcony. Moreover, while the plan of Palladio was equipped with eight large poles of square section for each of the four batteries, at about two centuries from the participation there were eighteen or more poles for single battery, because of the difficulties in the operations of substitution of the foundations, that pushed *proti* to employ poles of smaller dimension, but in greater number.

All along the XVII century the expirations, in which the books expenses of the bridge report the restorations executed on the single *stilate* and the radical repairs, were regular, but with the sweeping flood of October 1707 the bridge completely curved and it was necessary a complete reconstruction that started immediately.

«Deplorabile è la disgrazia succeduta la notte scorsa alle ore sette circa in cui l'impetuosa improvvisa escrescenza del fiume Brenta ha totalmente asportato il ponte grande» (*Official Records of the Council*, 19 agosto 1748); it was 19th August 1748, and the procedures of emergency for the construction of a temporary footbridge, in the vicinities of the Door of Brenta, started immediately. Contextually to the collection of the materials

draggled by the waters, a letter of the Doge (Pietro Grimani) informs us of a request for an estimate of expense to introduce to the Magistrate of Waters, on the base of the three plans written up for the reconstruction of the bridge.[5]

The plans of Tommaso Temanza, Giovanni Miazzi, and Bartolomeo Ferracina, triggered a debate on the «fabbrica suddetta che abbia nuovamente ad essere eseguita, com'era prima diretta, e disegnata dal Palladio, cui già ne conoscevano il modello.» (*Savi Esecutori alle Acque*, 30 agosto, 1748)

The cleaning operations on the gravel bed of the river revealed themselves immediately very difficult, because of the insufficient depth of *infissione* from the poles of the previous foundations, which opposed a strong resistance to every attempt of extraction. Searches addressed therefore on the possibility of constructing pylons in *pozzolana* instead of wooden *stilate*.

The Magistrate of Waters charged Giovanni Filippini and Matteo Lucchese, *proti ingengeri*, to study the feasibility of the wide supported plan, that unfortunately was never put into work, because of economic reasons.

Definitively discarded the hypothesis of piers in *pozzolana*, the plan was at first entrusted to the Magistrate of Waters, *proto* Tommaso Temanza, who was soon deprived of this authority by the self-taught Bartolomeo Ferracina, who guaranteed inferior expenses of reconstruction.

Examining carefully the complex vicissitudes of the eighteenth-century reconstruction of the bridge of Bassano it is quite clear that an ideological crash between the supporters of an aulic shape, reaching the Palladian orthodoxy, and the supporters of an empirical construction tied to the traditional wooden bridge occurred; finally, a common coding of the Palladian model was accepted. Also the singular solution of the pylons in masonry, of Lucchese and Filippini, is not substantially estranged to Palladian precepts.

It was only with the work of the mathematician Rizzetti, who produced for the bridge an original and innovative plan, that the real efficiency of the manufacture was put in argument. Rizzetti eliminated every imposed principle and rediscussed the consolidated image of the monument, and all the western tradition with it. The scientist, pushed by an Enligthened spirit, went away little by little from the typical stone constructions, which were too much expensive, and from the wooden ones, which were not much long-living, accepting as his study base the colourful descriptions of chain bridges, seen by catholic missionaries in China. For the bridge of Bassano he processed four versions of the same plan with a chain structure, describing in particulars the putting in work and the future upkeeps.

It was only with the definitive support to Ferracina that the hypothesis of the wooden bridge was finally and definitely adopted, a fact that deeply changed the aspect of what had become the symbol of Bassano.

Ferracina's bridge differed a lot from the previous ones, either in the constructive techniques or in the *partitura* of the spaces. The new position of foundation poles had disarranged the spans symmetry; the number of columns of the floor system was reduced to four per intercolumn, instead of the previous five. Between the strut node and the pole, the *tooth* of support was eliminated, in order to avoid an ulterior reduction of the section, which was already inferior if compared to the previous ones, and subdivided in two parts.

In this occasion, Ferracina realized a rammers machine, that guaranteed the minimal labour employment but created some problems because of the inaccuracy and the shunting lines that the poles met crossing the gravels.

Other typological variations emerge observing the profile of the bridge, on which a chestnut tree

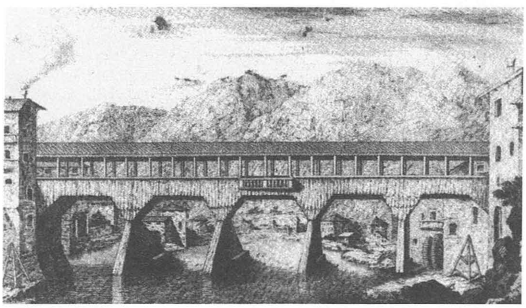

Figure 7
Il ponte di Bassano (The bridge of Bassano). Filippo Ricci (1752). In etching is represented the bridge in work during the second middle of the XVIII century; it is carried out on the plan of Bartolomeo Ferracina. (Archives Civic Museum of Bassano)

wainscot detached, completely covering the spurs and the flanks and pushing itself until the balustrade, according to the alpine use.

Anyway the discussions on the bridge did not diminish even after the work was finished, and negative judgments still continued to propagate after the opening of the new bridge.[6]

The chronology of the restoration jobs also proclaimed a negative verdict towards the new structure. The weaker parts of the bridge were the north forehead *stilate*, *the mantellata* and the bridge roof support columns.

The bridge risen from Ferracina's plan was destined to a short life, because it was destroyed definitively after fifty years although the frequent rearrangements.

Of the recent history of the bridge we must remember the construction of a temporary footbridge, before the idea of a real reconstruction was taken in consideration after the fire of 2nd November 1813 ordered by viceroy Eugene de Beauharnais.

Just afterwards the planning and directive jobs of the yard were entrusted to engineer Angelo Casarotti.[7]

The work for the new bridge begun in March 1819 and finished with the inauguration of 4th February 1821, introducing some important typological and structural changes, that substantially did not change its aspect in comparison with the Palladian manufacture.

The most important variation were not directly observable in the completed construction. In fact, it was in the foundations that Casarotti introduced an important innovation: the reconstruction, thanks to the use of new structural formulas for the support pylons, guaranteed a survival solution to the wooden manufacture through a differentiated load reaction induced by the sudden movement of waters. At the same time the engineer succeeded in conjugating Ferracina's unchanged *partitura* of the cover structure to the Palladian formal characteristics. Casarotti, moreover, *cut* the eight columns of the *stilate* near the water surface, and introduced the threshold beam in which there was a double order of pillings fixture in the gravel bed of the river. Seven poles were than added to the foundation of each *stilata*, passing from five to twelve poles for single foundation.

In this case the columns position is not so closely bound to the foundation poles, and becomes a guarantee of precision in the execution of the supports, reducing the difficulties during the maintenance operations. Moreover, the chestnut tree cover of the *mantellata* is completely eliminated remaining in reduced section only along the wire of the floor system, proposing again the old theory of side balusters deprived or the central balcony.

Thanks to the introduction of the variation in the foundations the new structure of the bridge, compared with the frequent destructions during the last ages, had a much greater longevity.

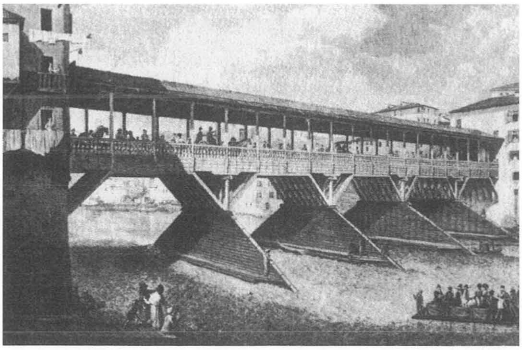

Figure 8
Il ponte di Bassano (The bridge of Bassano). Sebastiano Lovison (1826). The new bridge of Bassano recently reconstructed on the plan of the engineer Angelo Casarotti. (In Incisioni Bassanesi, n° 394)

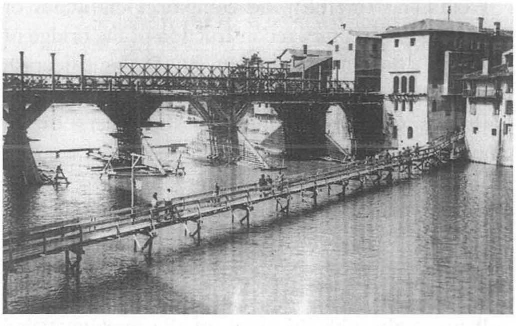

Figure 9
Foto del ponte nell'estate 1945 (A photo of the bridge of Bassano during the 1945 summer). Anonimo (1945). An imagine of the bridge after the German attack in Bassano during the Second World War; to testify the importance of the manufacture it can be seen a temporary footbridge in order to guarantee the connection with the city. (Archives Civic Museum of Bassano)

Casarotti's bridge resisted for more than a century, surviving to the enemy strafings in the First World War thanks to several restorations that were adopted with the usual, customary rhythm. It was instead fatal the partisan attack of 1945, followed by the complete destruction caused by German troops; nevertheless, the bridge was completely revived two years after thanks to *alpini*'s works.

The subject of the hardest work of reconstruction was the *stilata* of the bridge towards Angarano, which was entirely reconstructed, the two spans that supported it, the cover and the stony portal of Angarano side.

It is important to remark the complete substitution of the ancient riveting of union of wooden parts, with the introduction of a metallic fastener and threaded passing bolts; moreover, for the structurally collaborating elements, cylindrical wedges and slabs bites were introduced.

After the alluvium of 4th November 1966 a radical structural restoration was executed on the bridge by engineer Benetti; *stilate*, docks to trickle of water with the relative support poles, balustrades and practicable plain were reconstructed after they have endured the force of waters, that had caused the bending of the entire bridge.

Drillings for the construction of four poles were executed, upstream of each *stilata,* of 1,25 meters diameter, pushed to a 10,50 meters depth from the dock plan, in order to guarantee the stability of the bridge during the necessary time to complete the restoration plan. On the basis of the developed inquiries emerged a substantial difference of piling diameter between the data of the plan and the real situation. Moreover the poles witness were completely flaked and damaged on tip by the rammer blows, because of the encounter with a bench of consisting conglomerate, that prevented them to penetrate further down. It was certainly for this reason that the flood, after having dug the advanced gravel bench, had broken and thrown away with himself every support depriving the first *stilata* of the bridge of the necessary support, and it was necessary to demand a new type of foundation in order to protect the stability of the structure for the future.

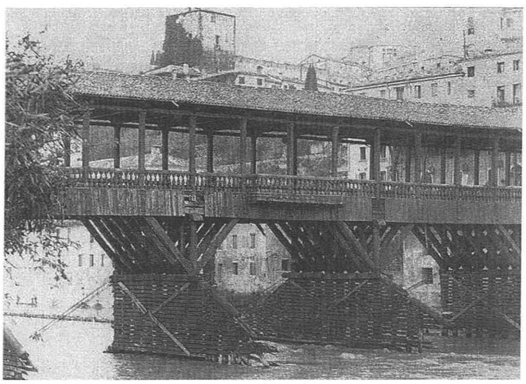

Figure 10
Foto del ponte danneggiato dall'alluvione del 1966 (A photo of the bridge damaged by the 1966 flood). Anonimo (1967). The damages suffered by the bridge after a Brenta waters bulge and the first interventions in order to straighten the *stilate*. (Archives Civic Museum of Bassano)

During the June of 1980 a series of restorations were considered necessary, as a result of an inspection of the support structures. It was a series of works of ordinary and customary maintenance because of the degradation produced by the usury and the severity of the weather visible through superficial analyses.

On the basis of more accurate analyses, followed up by verifications of the structures of the threshold, of the columns under the docks of the *stilate* ones, and the relief of 6th February 1981, the necessity of a wider plan emerged. An onerous situation came to the light, especially in the *stilate* towards Angarano where a sort of progressive damaging could be observed and elements seemed to have endured a greater degree of usury. The consolidation work operated during the 60's in the first foundation of the Angarano side was repeated on the remaining three *stilate*; new *cavazzali* were delivered up, resting on the poles constructed in 1966, using the new poles of dock fixed in the sides of each *stilata.*

Six years later the last jobs, the alarm was launched by the skin-divers of the civil protection who, engaging in a practice, noted a precarious state of conservation of numerous poles under the docks *stilate*. An anomalous lowering of the level of gravels was found, which favoured the abrasive action of waters near the foundation piers; therefore the historical foundations, although integrated with the new supports, did not guarantee the safety of the bridge. The pilling was in an advanced state of decay, and its tip was completely eroded, especially in the

Figure 11
I lavori del 1990 (1990 works). Ufficio Tecnico (1990–1992). To the left a particular of reinforced concrete pole tip and the conditions of the piling before the intervention; to the right the intervention on the damage a column with bars in *retroresina*. (Archives Technical Office of municipal of Bassano del Grappa)

central part of the *stilata*, and also did not guarantee the support to the threshold structures.

An ulterior macroscopic threatening element to the stability of the bridge was the vehicular traffic, that continuously subjected the structure to the dynamic action of vibrations. The situation of uneasiness in the section of the floor system was amplified by the same constructive characteristics of the practicable plain, because of the present fissures in the wainscot of the roof, that guaranteed the correct aeration and avoided the stagnation of the water on the overseer bituminous conglomerate, but also favoured the creation of funnel holes on the road-bed road, produced by the action of winnowing caused by the vibrations of the traffic.

The problem of the static functionality of the bridge system was joined by an unavoidable wearing down of the finished parts provoked by the atmospheric agents, a generalized ungluing of the assemblage nodes and a deterioration of the pictorial pigmented applications, that were joined by the progressive sliding of the cover mantle.

Because of the condition of elevated degradation the works directly begun in the river bed, through a general change of the carrying structure of the *stilate*. The new foundations did not visibly modify the aspect of the bridge, because the four poles for each single *stilata* are always immersed, also during the periods of lean of the river, and normally covered by gravels. The plan previewed a system of foundations on cement poles braces independent from the previous supports.[8] A wood bean, *cavazzale* of threshold, rests on each brace of poles.

This system of braces poles-*cavazzali* has the task to support the threshold, on which the eight columns for single *stilata* rest, carrying the bridge floor systems.

In the carrying structures the damages to the lumber were extended to almost all the elements, so it was necessary to demand the generalized substitution, a fact that would have involved the complete taking apart of all the bridge. In order to obviate the problem some recovery techniques of the ancient lumber was realized, choosing to repair the structural elements using conglomerates of epoxide resins and quartziferous sands in order to restore the great lesions, adhesives in pure resin for the small lesions

and bars in glass resin for the assemblage wood-conglomerate, and using wooden caissons for the reconstruction of the original shapes for the poles that presented some erosion symptoms.

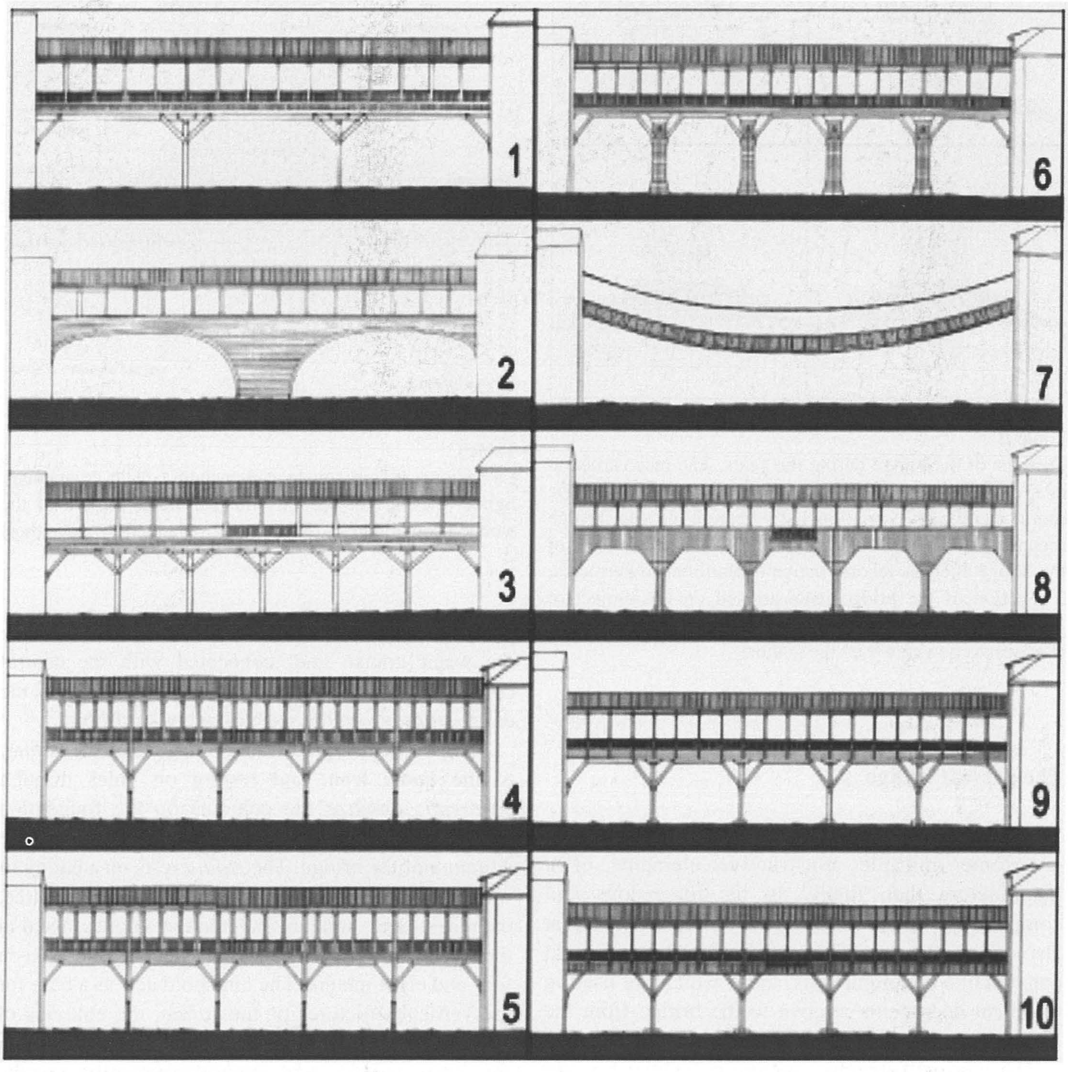

Table A
The section of the bridge during the years. The reconstruction of the section of Bassano's bridge through the documents, the plans, from 200's to nowadays: 1. The first wooden bridge, resting on two *stili*; 2. The stone bridge work between 1524 and 1526; 3. The wooden bridge resting on five *stili*, in work during the second part of 1500 and before the Palladian project; 4. The bridge reconstructed on the basis of Palladian's suggestions in 1570; 5. The bridge with the modifications in 1570 and 1748; 6. Section of the reconstructed bridge with pozzolana pylons on the basis of the project of Filippini and Lucchese in 1748; 7. The catenary bridge reconstructed through the descriptions of Giovanni Rizzetti in 1750; 8. The section of the reconstructed bridge on the project of Bartolomeo Ferracina in 1750; 9. The bridge of Angelo Casarotti in work after 1820; 10. The bridge after the reconstruction of *alpini* in 1945. (Reconstruction edited by the author)

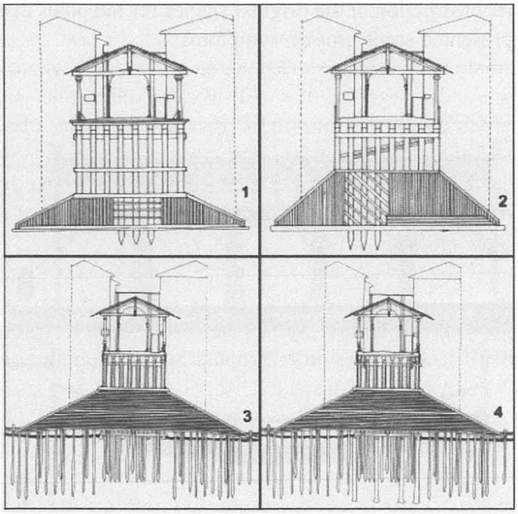

Table B
Sections of the bridge during the years. The reconstruction of sections of the bridge through the documents with the more significant variations: 1. Section of the bridge reconstructed on basis of the Palladian treatise; 2. Section of the bridge after the reconstruction of Bartolomeo Ferracina; 3. Section of the bridge reconstructed on the project of Angelo Casarotti; 4. Section ofthe current bridge. (Reconstruction edited by the author)

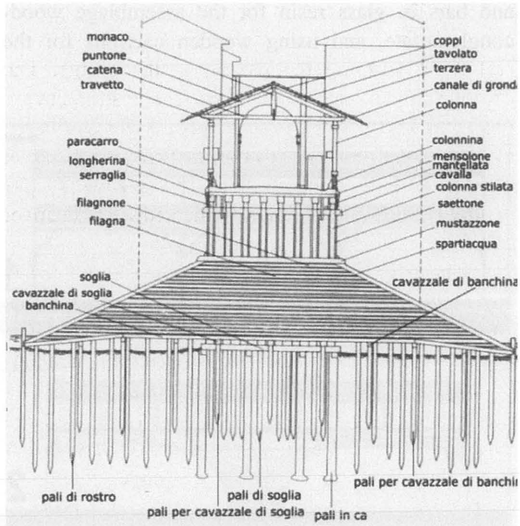

Table C
La sezione attuale con la nomenclatura delle componenti lignee (the current section with the nomenclature of the wooden components). (Reconstruction edited by the author)

The present bridge

The current description of the bridge allows us to pick out some multiple constructive elements of a manufacture that, thanks to its dimensions and complexities, is still today rare and precious, and that also gives the occasion to recall the traditional constructive denominations: those which are used in technical documents relative to the bridge from the end of the last century onwards.

The vertical carrying structure is formed by four *stilate* supporting five spans, accompanied by the two masonry shoulders, on the east and west side. In each single *stilata* various functions can be distinguished: the central part, directly carrying, where the weight of the bridge is transmitted from the columns to the foundation threshold, and from this to the fixture poles, whether with directed support, or through three or four *cavazzali* for each *stilata*; the two external parts upstream, *rostri*, have instead the task to cleave the water course and, connected with the central columns, to strength, through *filagne* e *filagnoni*, the entire *stilata* from the push of waters in flood.

The two docks, placed on both sides of the *stilata*, to the quota lean, and resting on poles through *cavazzali*, stabilize the columns on the foundation threshold, allowing the access from the bottom to the structure of the bridge. The *stilata* rests on a paling of wood elements of old locust-tree, larch, chestnut tree, the oldest ones, and bay oak, the recent ones, fixed in the river bed of the river into a variable depth between four and eight meters. The threshold acts as a base for the vertical structures of the *stilata*, the columns of chestnut tree, bay oak and larch. The columns, eight for each *stilata*, are erected vertically on the threshold, and carry out a support activity for the horizontal structures of the floor system of the bridge, those of its plan of stamping, and for the cover.

On the top, in the columns that rise on the part just described, a large beam, *cavalla*, is placed horizontally, joining them to form the support for the true floor system spreading up amongst the four *stilate* and the contiguous building structure of the

incomes to the bridge, from Bassano to Angarano. The horizontal structures of the five spans work as the real floor, forming the paving of the bridge. The external parts of the described horizontal structure are protected by the *mantellata*, in vertical tables of larch, that extends from the advanced share of the street plan to the inferior one of the *serraglie*; the *mantellata* is articulated and connected with the cover columns by shaped vertical modillions.

Connected with the kerbstones rest the vertical larch columns of the cover, amongst which the *colonnine* of the balustrade are arranged. The advanced extremities of the columns are all connected by horizontal beams, *dormienti*, to which the simple four elements trusses are placed supporting the longitudinal *terzere* and the overseer larch floor system, to whom the cover mantle is overlapped.

Conclusions

The detailed study of the history of the bridge, joined to the analysis of the several methodologies of recovery that in the course of the centuries have followed, brings to an important and fundamental consideration: for all the time a simple and systematic maintenance work has allowed to extend the life of a fundamental work for the Italian architectonic patrimony.

The considerations carried out on the historical document base, or less, on plans, iconographies, on maps, become a useful source of increase of the acquaintances compared with the methodologies that today still can be considered feasible. Only the perpetuation during the centuries of ancient techniques has allowed the maintenance of the structure like it is today, but at the same time the graft of new workings becomes a reflexive cue if compared with the possible methods of execution of restorations and maintenances, thus creating the necessary bases in order to face a plan on a wooden structure. The plan of maintenance of the bridge must comprise, beyond the fundamental characteristic of preservation of the wood in work, also the eventual consolidation and reintegration of the masonry shoulders, and the cleaning of the stone doors.

These are the motivations pushing towards a programmatic analysis of pathologies, and of the participations to execute, because often delays of two or three years in completing the jobs have brought to situations in a so advanced degradation that prevented a re-adaptation of the old wooden elements. An organic and comprehensive plan of feasible techniques on wood, in order to supply the bases for the conservation of the manufacture that is currently in work, without the necessity of creating a plan of a work in the river bed.

The visual examination remains the fundamental instrument for the analysis and has allowed to determine some symptoms of disseminated degradation; but in order to obtain some certainties on the real conditions of the lumber it must be executed some orchestrates analysis, choosing between the less harmful methodologies for physical integrity of the constituent lumber. Endoscopic examinations and the usage of ultrasounds are useful in order to determine the volumetric mass and the discontinuities of the woven, that can apparently look as in a good state of conservation, but could otherwise induce also the more expert students to misleading results.

The survey of the main symptoms of degradation of the wooden material constituting the bridge of Bassano goes executed through a specific source of alteration; subdividing pathologies due to the attack of microorganisms, that find a particularly favourable atmosphere, from pathologies of physical and chemical origin and from the degradations of structural origin.[9]

If in the past in order to protect the surface of the wood the linen oil and the virgin wax of bees have been used, or as in the times of Ancient Rome, practicing holes in the wood in order to inject oiled liquids, during the years, the technique has been sharpened; in recent years, the use of a more effective mixture composed by oil and linen oil guaranteed a durable protection, while nowadays synthetic or microcrystalline waxes are used, to whom fungicides and bactericidal are joined, applied uniformly on the surface to protect the wood; in alternative innovative methodologies are added to the usual procedures always employed to preserve the wood; the technique of protection with water base varnishes becomes in this context a possible answer to the ecological problems of using strongly polluting and dangerous solvents. Substantially all the studies that have been carried out, tend towards the will to recover and to maintain the ability of usage of the whole structure, in

order to make it enjoyable in the best way for the next years, and opening this way a debate on the best methodologies to adopt for a plan that cannot be delayed anymore.

NOTES

1. Medoacus Major, Brenta's Roman toponym crossed the primitive nucleus of Marostica and Sandrigo until it met Medoacus Minor in the Bacchiglione, that through the centuries has slowly moved its river bed towards east in the plain area, nowadays spreading from the Astico and the Tesina, in consequence of a process of Adriatic coast's hollow isostatic lowering, which is common among Venetian water courses.
2. In the first mountain section from the lakes of Trento, Levico and Caldonazzo two small torrents exit, giving origin to the Brenta; the river covers approximately seventy kilometers within the slopes of mounts. The water, penetrating in depth through the karsts systems ascends in surface, in correspondence with the sources of Oliero, north of Bassano, and enters the high plain. The course of the river from Bassano to Piazzola is characterized by the channels interlaced morphology, whose changes can be observed confronting the technical papers of various periods. Usually the floods corroded the islands until they made them disappear, or increased them, until they reached a certain stability. In this case a vegetation with plants to medium stalk develops, typical of the ecosystem we are analyzing, like poplars and locust-trees. Usually the channels are introduced as spoon shape, with sand in sides and on the bottom destined of being removed during a successive flood, while *limi* and the fine sands are deposited in sinkings of the abandoned channels. The last section of the river from Piazzola, lapping Padova eastwards, until it flows in the Adriatic Sea near Chioggia, assumes the characteristics of a meandri system. The last section is subjected to a reduced ability of waters transport, where the fine materials make thinner, because of the typical handles course and the insufficient slope that meets in the territories.
3. The decisional tasks belonged to the Council of Ten and to the Senate, until the constitution of a permanent and ordinary Magistracy composed of three nobles who had to protect waters.
4. These payments represent a reliable source, for the historians, in sanctioning the existence of two plans; the first balance referred to the labour of the first captured model, and the second one, slighter than the first one, for another model wanted by Palladio in order to bring modifications in work course, as suggest Puppi (1996) and Zorzi (1966). Temanza (1770) supports that the first palladian design can be identified, in 1568, as a «*inventione*» for a stone bridge with three arches, mindful of the shapes of the roman bridge in Rimini, published in the CAP. XIV of the Third Book, without any specifications about the place whom it was destined; according to Maria Azzi Vicentini (1980), the artist had the possibility to prepare a table of the Four Books, dedicated to his ill-fated invention, and at same time to introduce in the presentation some important indications in order to reveal the place on which the factory had to rise, confirmed also by explicit silent of the locality for which the plan had been conceived
5. A competition for the reconstruction of the bridge was proclaimed and three plans were introduced: the first one by the Magistrate of the Waters, promo, Tommaso Temanza; the second one by the engineer Giovanni Miazzi, who was entrusted to construct a temporary footbridge by the Podestà; the third one was presented by the self-taught Bartolomeo Ferracina.
6. A real campaign against Ferracina was carried out in the city, due essentially to the will of the engineer of Solagna, who provoked the dissatisfaction of the hands, the resignations of some Presidents named by the City Council, and dissidences between the common citizenship. Entering upon the subject, that will have Poleni, Temanza, Pilippini, Miazzi and other illustrious personalities of Bassano involved, the interest in the reconstruction increased among Venetian architects, engineers and scientists.
7. Some years passed before the idea of the reconstruction was taken in consideration by municipal; so spontaneously the population of Bassano collected the necessary funds for a reconstruction.
8. The new foundation was constituted by a piling with four braces of cement poles, 10 m deep approximately and a 58 centimeters diameter, armed by stainless steel and covered by metallic sheet.
9. Examining the degradation of wood, pathologies has been subdivided according to their source: biological degradation, caused by microorganisms (sub-orthogonal disintegration, presence of vegetation, biological patina, superficial warehouse, pitting, chromatic alteration, lacuna); chemical and physicist decay, caused by the exposure to the solar beams and to the atmospheric agents (wrinkling, crackle, marcescence, spot, erosion); mechanical degradation, of structural origin (helicoidal lack, deformation, cracks, rigid clefts along the fibers, translations, cleavage, spins).

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On the origin of modern timber engineering

Mathias Seraphin

The depression at the end of World War I forced German civil engineers into timber construction which had almost been ignored in the second half of the 19th century. Within a few years methods of engineering were applicated to traditional carpenters' woodwork. They faciliated new wide spanning truss and arch constructions based on joints that reduce the joint-slip to a minimum. In building storehouses for chemical industry, railway engine sheds and antenna towers timber construction becomes even superior to steel construction. In the 40's, timber engineering was part of the upcoming standardisation of construction in Germany.

PROTO-TIMBER-ENGINEERING

Up to the 1850's, wood has been the standard material for light wide span constructions. Thus the most important inventions in construction at the beginning of the 19th century were originally timber constructions with additional parts made of steel: laminated arches, elliptic and suspended beams and various truss girders. Particularly the girders by Howe and the suspended beams by Wiegmann and Polonceau may be looked upon as if designed by engineering means, a kind of proto-timber-engineering.

At that time, Modern engineering developed mainly as the result of three events: 1. the transfer of natural science into building practice initiated by the foundation of technical schools in France; 2. the evolution of metallurgy in England that supplied the industrialising countries with cast iron, later with steel at low costs unknown before; 3. the new types of construction created by North American carpenters evoking the theories of framework set up simultaneously by Whipple, Culmann and Jourawski (Whipple 1847; Jourawski 1850; Culmann 1851).

Straub (1992, 287) considers this event as the break-through of modern engineering: «In establishing graphical statics a progression had been completed in a certain way, an aim had been achieved: static behaviour of the most important structural principles in construction had been mainly cleared, engineers were enabled to design their buildings on scientific principles».

In about 1865, modern engineering is constituted, steel had replaced wood in almost all wide span constructions like bridges and halls. Meanwhile, mill technology and ship building, for hundreds of years «high end» timber construction, have become a domain of steel as well. Carpentry was reduced to its basics: floors and roofing. Around 1900, seldom used truss girders according to Howe and laminated arches according to Emy remained as poor heritage examples of the creative époque around 1850.

START-UP 1900

As a reaction to workers' unions that appeared in the 19th century, carpenters in Germany began to

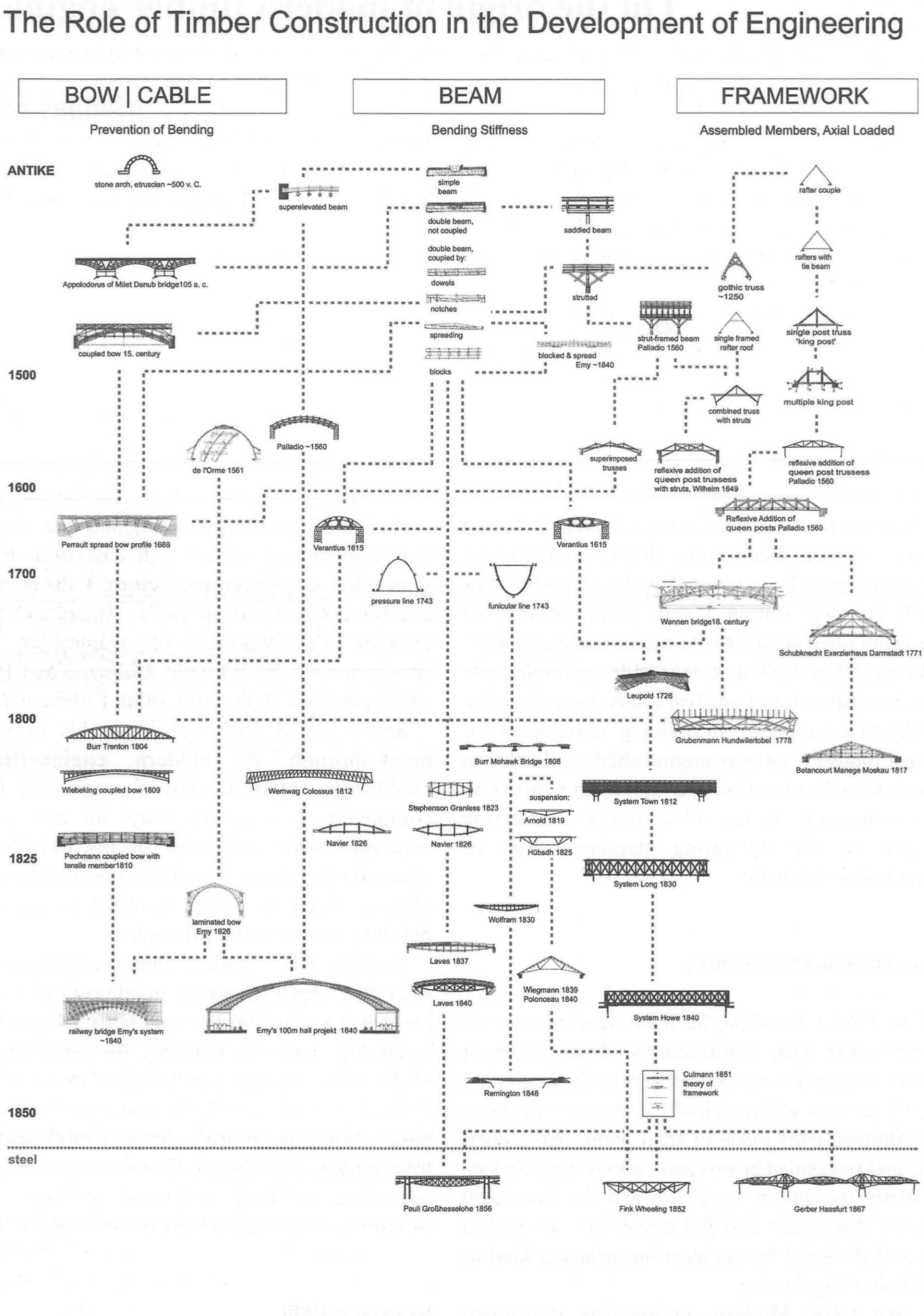

Table 1
The Role of Timber Construction in the Development of Engineering

reorganise themselves by the turn of the century. It was at that time, when some German carpenters and architects started experiments on new forms of timber construction, using engineering methods of calculation. (NN 1907, vol. 25, 2)

After 1890, Philipp Stephan, an architect from Düsseldorf, succeeded in bracing slender arches by using crossed struts to avoid buckling, followed by other enterprises like Carl Tuchscherer, Breslau experimenting as well with solid web profiles (NN 1902, 195; Kersten 1921, 50).

In 1904, Paul Meltzer from Darmstadt started building girders of bundled lattice-work fixed by steel pins. In the beginning, he used Australian Jaraah hardwood, later European and American pine as well (Zipkes 1914, 406).

Based on a patent of 1906, Otto Hetzer a carpenter from Weimar developed casein-glued laminated timber bows and trusses. Due to very successful marketing and international franchising, Hetzer-girders became very common all over Germany, Switzerland, scandinavia and the Netherlands (Hetzer 1907).

Around 1910, enterprises like Adolf Sommerfeld in Berlin, built timber-steel-framework based on Howe's principles using adjustable steel elements for the tensile parts of the construction and wood for the elements in compression (Gesteschi 1919, 89).

The Railway Impulse

In the beginning of the railway, the main buildings and bridges were built of wood for economic reasons. Before the success of the new transportation system, construction had to be achieved at low costs and in a short time. Later, more representative stations were built of stone with halls of steel and glass. Wooden bridges were replaced due to fire prevention in North America and Europe before the end of the century. In 1937, the last regular wooden railway bridge in England was taken out of service (Brown 1994; Brockstedt 1994, 101; Dietrich 1998, 106).

On the other hand, the lack of corrosion resistance against engine fumes and the high costs of maintenance soon became obvious. A milestone was the «Reichseisenbahnhalle» for the 1910 World Exhibition at Brussels built by Hetzer which had lamella frame girders of 43 m span. In 1912 the Swiss Railroad Company ordered a central engine hangar at Bern and advised all subdivisions of the company to use timber instead of steel for halls and hangars. In 1913, Kopenhagen Central Station was built with wooden halls by Philipp Stephan. These halls still exist like those at Malmö from 1922 and Stockholm from 1925 built by Hetzer (Mannheimer 1910, 206; NN 1913, 289; De Bruyn 1913, 377; 1994,79).

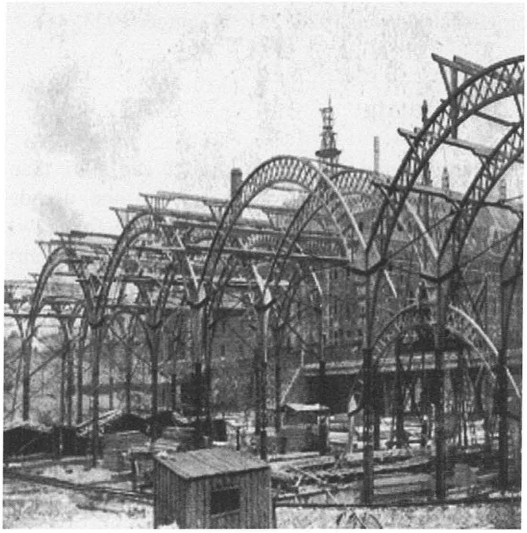

Figure 1
Kopenhagen Central Station by Stephan 1913 (Kersten 1921, 64)

During World War I the work on the halls of Stuttgart Central Station had been stopped. After the war, work was continued on the halls, for economic reasons however, not in steel, as planned before, but in timber construction. Karl Schaechterle, responsible for the construction department of the Württembergische Staatsbahnen, at that time and, after 1918, of the united Deutsche Reichsbahn, initiated scientific studies on timber construction linking the practical knowledge of Karl Kübler AG from Göppingen with the theoretical and experimental possibilities of the Materialprüfanstalt, associated with the Stuttgart Technical University nearby. The studies were proceeded under the leadership of Otto Graf who took the heritage of August Lang, from Hannove,r who

was the first to do scientific experiments on wood as a construction material. As a result, the «Preliminary Specifications on Timber Constructions» of the Reichsbahn were issued in 1926, the precursor of DIN 1052 from 1933 (Graf 1922; Schaechterle 1921, 33; Schaechterle 1927).

Corrosion resistance against acids and bases makes timber a preferred construction material in chemical industries and salt mining. Wood is widely used for hangars, bridges, water and conveyor towers, even for pipelines (Kersten 1926, 231; Waninger 1923, 45).

Ground to Air

Spanning around 30 meters in width and more than 100 m in length, airship hangars for one decade became one of the top challenges for civil engineering. At the 1909 Internationale Luftfahrt Ausstellung in Frankfurt, some timber airship hangars were displayed. Brockstedt listed 24 wooden hangars, nine of them by Ambi (Arthur Müller, Berlin). All the well known timber entreprises present projects, even though most of them were not realised (Dean 1989; Brockstedt 1994a). Schütte-Lanz even built the frame of their lighter than air ships with asp plywood. Similar to Hetzer's caseine glue Schütte used glutene glue based on cattle blood (Schütte 1926). Sonntag asserts in 1912 (p. 606): «The needs of competition have lead to a more careful treatment of details, to new designs and to new ways of utilisation of timber material and forms, known before only from iron constructions. The progress in knowledge on statics and strength of materials versus handcraft has been successfully pushed by the construction of airship hangars».

Beside the airship hangars Hetzer, Sommerfeld, Ambi, Meltzer, Stephan and Tuchscherer built lots of

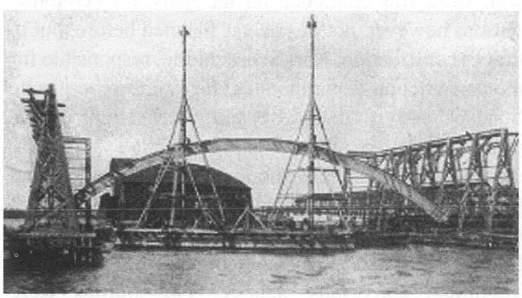

Figure 2
Waterplane hangar by Tuchscherer (Kersten 1921, 109)

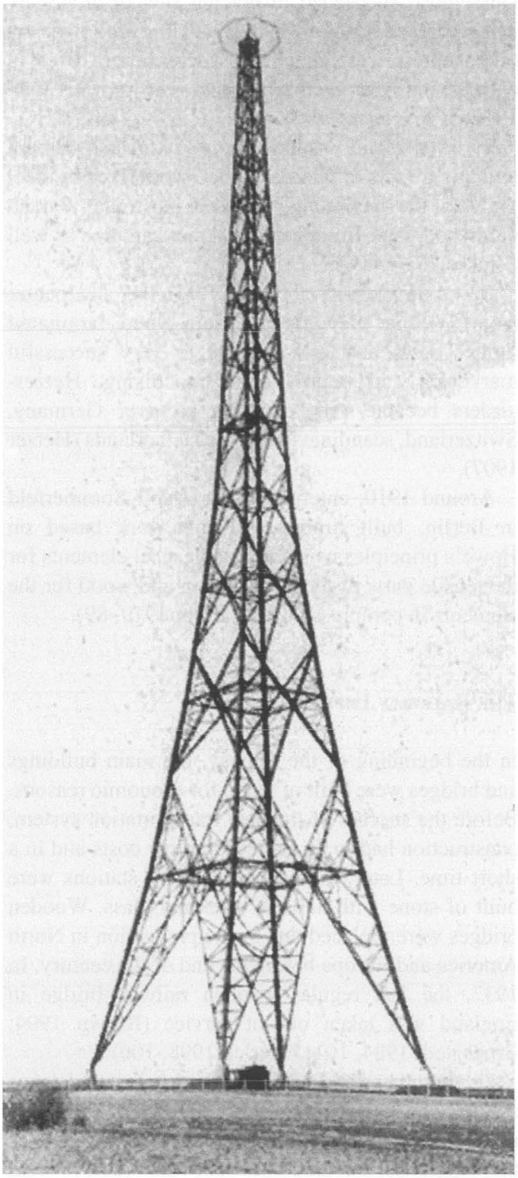

Figure 3
Mühlacker broadcasting antenna tower (Traub 1034, 491)

wooden aircraft hangars, supplying the airfields of World War I (Sonntag 1920, 111). Moreover, as an electric isolator, wood was superior to steel in broadcasting constructions up to the 1930's, when wooden antenna towers reached 190 meters in height (Traub 1934, 485; Leiter 1933, 487; Föppl 1933, 305).

Timber Construction in and after World War I

In supplying the army of the German Empire during the World War, innovative structural designs beyond the constraints of legal and administrative regulations were attained by the timber construction companies. New designs that relied on engineering principles, lead to interim bridges and to wide span hangars for airship and aircrafts avoiding steel, which was claimed for weapons. Civil engineers gained experience with temporary timber construction that had to be build for heavy duty and as quickly as possible to repair damaged bridges for railways and streets. Timber was the preferable material because of its general availability and the easy and fast handling.

There was also a strong impulse towards standardisation concerning the entire war economy, including the construction sector. Part of the Hindenburg-Plan was to increase the industrial production of weapons, ammunition and other warfare by unifying standards. Based on these ideas, standardisation continued after the war spreading as well into non-industrial sectors of the economy. DIN meaning Deutsche Industrie Norm got a wider, new signification: Das ist Norm (Schaechterle 1943, 36).

The unfortunate end of World War I brought Germany into a deep depression that forced engineers into timber construction, forthey were too short on energy to produce steel, concrete or even bricks. The timber experience during the war served to establish a multitude of new timber construction companies in the years following 1918. Documented in lots of patents for special dowels, in the early 1920's, timber construction regained a competive position towards steel construction (Kersten 1921;Jackson1921; Seitz 1925).

What is the Characteristic of Modern Timber Engineering?

The specifics of timber construction lie in the use of engineering methods of calculation and the implementation of mechanical fasteners made of steel to reduce the traditionally tall joint slip in wooden construction (Lewe 1922). Special glue is used to build more or less homogeneous profiles of a bigger size than given by natural sources. Both means allow to build composite profiles that can compete against steel trusses in terms of span and loads.

Dowels and fasteners can be classified by their material, their cardinal strain, i.e.: tension, compression, shear or bending, their geometry and their stiffening or articulating effects on the static model. The implementaion of modern steel connectors in timber construction was due to the benefit of the invention of the portable power drill.

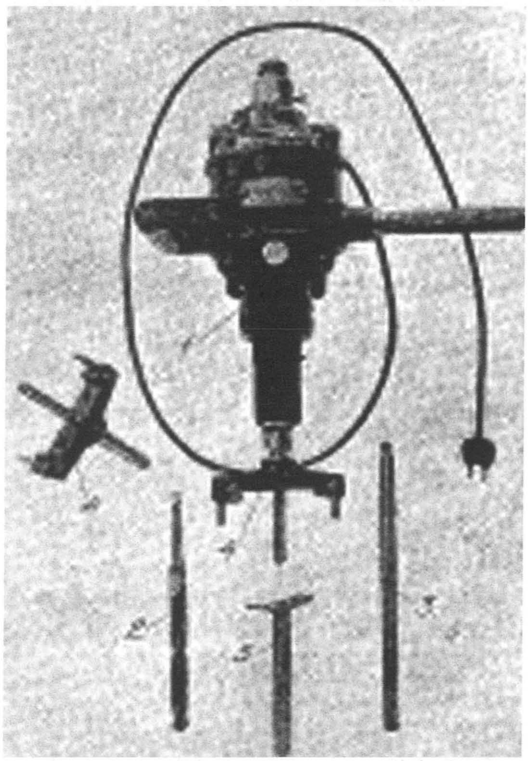

Figure 4
Drill centered fraise (Nordell 1919)

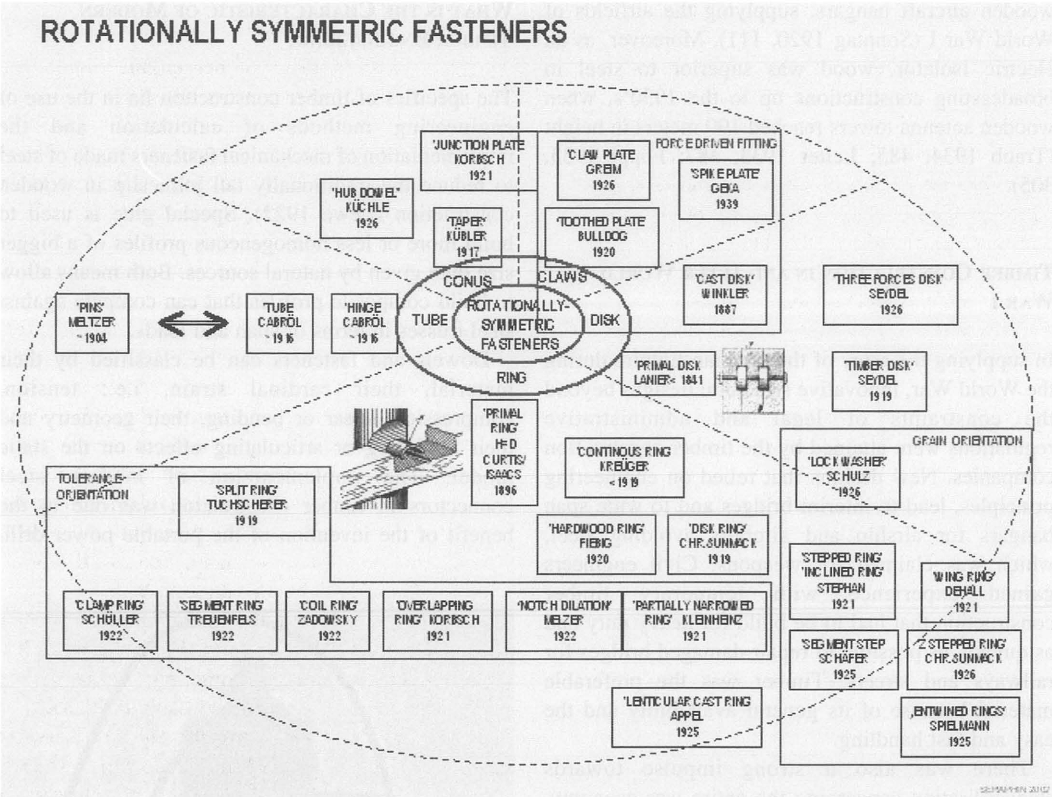

Table 2
Rotationally Symmetric Connectors

With drill centered fraises, accurate recesses became possible that allowed the proper fitting of the connector. The arrangement, axially symmetric to the leading bolt, forms an ideal pin. The handheld drills allowed to work true to size, even on the construction site, in assembling the parts (Nordell 1919; Seraphin 2002).

Establishing a Technology

The reorganisation of the German society after Versailles gave industries the opportunity to proceed in standardisation by installing the group for unified technical reglementation at the board of normalisation of the German Industry (ETB —Einheitliche Technische Baubestimmungen— Ausschuss im Normenausschuss der deutschen Industrie —NDI) The newly founded «Deutsche Holzbau-Verein» succeeded in representing the concerns of modern timber engineering. In the beginning, practical knowledge met theory in a manner of misunderstanding (Sommerfeld 1920).

The growing awareness of the problems timber construction has had to face, due to a series of spectacular collapses, would probably have defeated a useful standard, simple enough to be practised, if not Schaechterle had managed to find rules for railway buildings based on the Stuttgart Central Station. The 1926 «Preliminary Specifications on Timber Constructions» of the Reichsbahn were followed in 1930 by DIN 1074 «Bridges in Wood» and finally in 1933 by DIN 1052 «Construction in Wood» (Seitz 1925; Schaechterle 1926).

Between 1918, the year of the boom of inventions, and 1933, the year that DIN 1052 was issued, modern timber engineering made up for some 50 years of ignorance. In a rush, wood construction regained competive qualities against steel and concrete.

The following decade was dedicated to the consolidation of the findings by scientific tests on timber. Timber engineering research has been strongly supported by the authorities of the «3rd Reich» to reach autarchy. Like in the former imperial era, construction of temporary bridges —now built by nailed boards— was a key task to armanent in the 1930's. And normalisation provided the structures for this process.

After several updates based on research, particularly on dowel and nail joints by the Technical Universities of Stuttgart and Karlsruhe the German standard DIN 1053 achieved in 1943 a status that kept its fundamental validity up to the actual conversion into European standardisation (Graf 1944; Schaechterle 1943, 36; Wedler 1944).

The Protagonists of modern Timber Engineering

Carpenters, architects and civil engineers participated in the evolution of modern timber engineering. that was performed by companies, not by single craftsmen. Some of the leading companies were or became public incorporated.

Many construction enterprises got involved in timber construction after the war from 1914–1918. Getting out of the worst depression, some of them, for example Hünnebeck, dropped their timber activities as soon as possible, some of them like Karl Kübler AG or Siemens Bau Union continued work in an special timber department.

Most of the companies were acting nationwide and some of them like Hetzer and Christoph & Unmack may be looked upon as early global players, trading aircraft hangars and prefabricated houses and barracks all over the world. Companies installed a system of franchising, with local carpenters being partners of the license owners. In order to convince the public of their systems, designers published lots of examples and often even the caculation schemes in engineering journals (Christoph 1926; Lewe 1920).

Foreign Affairs

The genesis of modern timber engineering in the beginning 20th century, appears initially as a German affair. In contrast to the development of engineering in the 19th century, being the result of French, British and American impulses, the foreign influence on timber engineering was negligible. On the other hand German timber construction showed soon remarkable effects in scandinavia, the netherlands and in switzerland. For the Baltic region the technical universities of Riga and Danzig took an active part in the process.

In France and Great Britain, the adoption of steel and, later, concrete construction in the 19th century was more complete than in Germany. Conversely the resistance against modern timber construction seemed to be rather strong. So a renaissance of timber construction cannot be detected there until the 1950's.

Refugees from Nazi-Germany, first of all Konrad Wachsmann and Walter Gropius, started to proclaim modern timber construction in the United States of America in the 1930's. Max Hanisch, who had emigrated from Weimar some ten years before, established the American glulam industries in Wisconsin at that time, using the Hetzer system of caseine glue. Gesteschi reported several reconstructions of suspension bridges in Oregon, in which stiffening Howe trusses were toughened by ring dowels. Already in 1927, the St. Louis Fair built a hall of 60 metres span in Zollinger's lamellar space structure that persisted as a baseball arena until 1999.

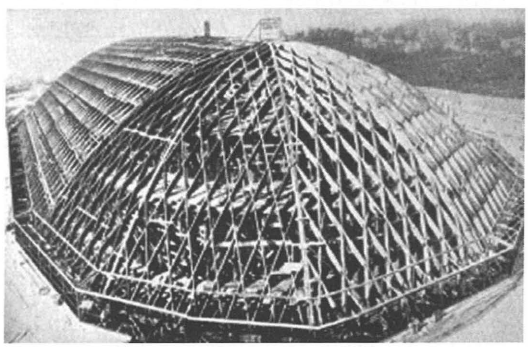

Figure 5
St. Louis Arena under Construction System Zollinger 1927 (Bayerische Hallenbau GmbH 1929, 28)

After the Pearl Harbour attack, the US created an aerial surveillance by airships operating out of 17 identic wooden hangars along the east and the west coast. Measuring 331 metres in length and 90 metres in width they were the biggest buildings made of wood up to now. Some of them still exist (Grüning 1989; Rhude 1995; Smith 1999; Dean 1989).

Timber Construction and Modern Architecture

In 1920 Walter Gropius, the director of the Bauhaus at Weimar praised timber construction as a chance to regain a sense for building « . . . the broken world will revive-newly formed by our brains and hands . . . Wood is the building material of the present, the one of the distant future, the one of our wishfulness — pure glass— we won't have reached maturity until the sense of building will have animated the entire people such as it was during the period of the gothic cathedrals (Gropius 1920)».

In reality the plight is more prosaic. It was a big frustration for Paul Bonatz when the pre-war design of the halls of the Stuttgart Central Station spanning around 40 metres was altered into a 20 metres spanning construction based on continuous beams to reduce the converted space and thereby the costs. «from the architectural view the substitution of the iron halls by wooden halls is not only unobjectionable but the wooden halls are definitely preferable for their special attractiveness. . . . It is essential indeed, to choose the 40 metres hall and not the 20 metres hall». The architect's opinion had been simply ignored lately. Astonishingly the halls had been reconstructed after the damages of World War II in the same appearance, but then in steel. The abdication of high halls and the installation of flat halls with fume outlets is a type of railway station that became common until the actual rennaissance of the big halls. (Schaechterle 1921; NN 1921).

The bigger part of the buliding projects is handled as purely functional: storehouses in industries and railways, antenna towers for broadcasting, hangars for aircrafts and airships. The contractor himself manages the entire project representing engineer, architect and executing company at the same time.

Due to the economic situation decoration takes a back seat in design, compared to the pre-war period.The achieved distinctness of the structural design affords the opportunity of an unostentatious classiness in appearance. In particular the slender bow designs by Stephan and Tuchscherer, the cambered frame trusses by Hetzer and the filigrane lattice work by Meltzer sometimes were of excellent esthetic quality. One of the most impressive examples is the Westfalenhalle, built in 1925 at Dortmund with 76 m in span (NN 1925).

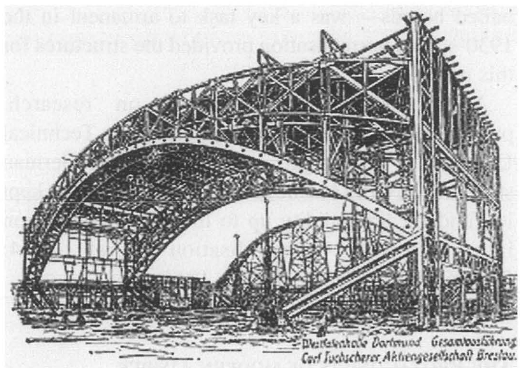

Figure 6
Construction System of the Westfalenhalle in Dortmund 1925 (NN 1925)

Except Conrad Wachsmann, who took an intermediate role between architects and engineers modern arcitecture and the Bauhaus avantgarde do not seize the regained possibilities of the old material. Wood has still the aura of regression at that time.

Conclusion

The disastrous situation in 1918, forced German engineers to resort to new ways of construction in wood that had been a forgotten material for about 70 years. Within a few years, methods of modern engineering were applied to tradtional carpenters' woodwork, restoring its competitiveness by reducing the joint-slip by special dowels, fasteners or glue. The development that took place in Germany between the World Wars defines the birth of modern timber engineering.

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Structural analysis of an outstanding historical building: New insight into its construction history

Marina Šimunić Buršić
Peter Ferschin

The development of the constructional concept and details was a slow, step-by-step process —until the modern era of fast technical progress. In the past master-builders learned their skills from their predecessors. As the forms, spans and structural solutions changed slowly, they were able to apply their knowledge, acquired by observing pre-existing structures, to the structures they were actually building.

But there are some outstanding buildings, which made a giant leap in the history of construction with their original constructional and structural concept. These buildings, if their innovative concept proved to be structurally sound, became the origin of a new tradition —or remained isolated examples.

One of these isolated, unique structures is the cathedral of Šibenik, Croatia (began 1431 - completed 1536). The construction was carried out by unexceptional Venetian masters, when in 1441 a major structural problem appeared. Only in 1443 the construction was resumed, guided by a new *protomagister,* George the Dalmatian. He solved the structural problem and constructed the eastern part of the church in a new way. While the walls of the western part of the cathedral, built before George the Dalmatian, are constructed of stone blocks masonry, the apsidal part is built using specific technique of assembling large stone slabs into the stone «frames».

Nicholas the Florentine, *protomagister* of the Šibenik cathedral 1477–1505 (after George the Dalmatian's death), adopted the specific constructional method of the apsidal part and applied it to the barrel and semi-barrel vaults of the church. Thus he created an original vault system: the webs are assembled of long, thin stone slabs, wedged into slender stone arches. These vaults are much lighter than usual massive barrel vaults, and, unlike masonry vaults, transfer their load mostly to the arches. As the arches are tightened with iron tie-rods, their horizontal thrust does not affect their slender substructure.

This structural system is unique. Precise and original details, rediscovered only ten years ago, during the disassembling of the dome (damaged during the war in 1991), prove high skill of Dalmatian stonecutters in the time of Renaissance.

We researched the mechanical behaviour of this original, daring structure. In order to research the construction history of the cathedral of Šibenik, we analysed both historical documents and mechanical response of the structure in several building phases. This approach provided interesting insight into the mechanical characteristics of the building and into its behaviour during the construction, and inspired new hypotheses about its construction history.

Development of structural systems in history: Tradition and innovation

The history of architecture is inextricably connected with the history of construction. The architects' idea of space and form cannot be materialised but through

the construction of a structure. Development of structural concepts, and not the changing of fashion in decorative forms, is the driving force of the history of architecture.

Tradition

In the pre-industrial, traditionalist societies, the generally adopted concepts of architecture, considered both as a spatial art and as a technique of building, were also an element of the identification of the society's traditional values. Of course, only the architectural concepts that justified and proved their structural logic by a simple fact of existing for a long period of time, resisting all the usual and even unexpected impacts (such as earthquakes, strong winds, extreme temperature variations), were commonly adopted as good and reliable.

Following the common sense, the constructors of the traditionalist societies applied good old «time-proof» solutions to the new constructions that they were actually building. Indeed, why change the solutions that already proved their qualities?

Of course, in spite of this conservative, but logical approach, every building imposed specific requirements: larger spans, bigger openings, **a new building material,** specific requirements due to the gradual social change which resulted in a different way of life . . .

Thus, the structural and constructional solutions did change in time, but very slowly. Due to this fact, the master-builders of the past were able to apply the skills and knowledge acquired from their predecessors to their specific problems.

It is well known that the ancient masters did not know the theoretical laws of mechanics. The theoretical concept of mechanical force was not developed until Sir Isaac Newton's axioms, which built a basis of a new, consistent theory of physics (17^{th} century).

Nevertheless, the structures that great architects constructed throughout history —daring, logical and resistant— testify that they understood perfectly the mechanical behaviour of their structures. Their thorough insight and understanding of structures was based on the empirical knowledge, gathered in centuries-long tradition of building in the same or very similar manner. In fact, their knowledge was truly experimental —they observed existing buildings, their mechanical behaviour, possible weaknesses or occurrence of cracks, and applied this experience to the structures that they were actually building. And more, as the construction process was relatively slow (mediaeval cathedrals were being constructed for centuries), they were able to observe their own buildings, their behaviour and weak points, and to intervene if necessary. Thus, the real, existing buildings were their full-scale models (Mark 1982, 9).

Exceptions

The slow, step-by-step development process, in which new structures only slightly differed from the existing, time proved paradigms, was a usual way of development of structures and methods of construction in the past.

On the other hand, there are also some outstanding structures, with amazingly new and radically different solutions of technical and formal problems —the outcome of an ingenious concept and skilful craftsmanship, supported by an enlightened investor.

Such outstanding buildings, if their innovative constructional and structural concept proved to be structurally sound (which is simply empirically proved by their resistance to all the impacts that they were exposed to during their life-cycle), became the origin of a new tradition —or remained isolated examples.

The cathedral of Šibenik

One of these isolated, unique structures is the cathedral of St James in Šibenik, Croatia. In the year 2000 this masterwork of the Quattrocento architecture was inscribed into the UNESCO World Heritage list, primarily because of its « . . . structural characteristics . . . which . . . make it a unique and outstanding building . . . The Cathedral of St James is the fruitful outcome of considerable interchanges of influences between the three culturally different regions of Northern Italy, Dalmatia, and Tuscany in the 15^{th} and 16^{th} centuries. These interchanges created the conditions for unique and outstanding solutions to the technical and structural problems of constructing the cathedral vaulting and dome». (UNESCO 2000, 43)

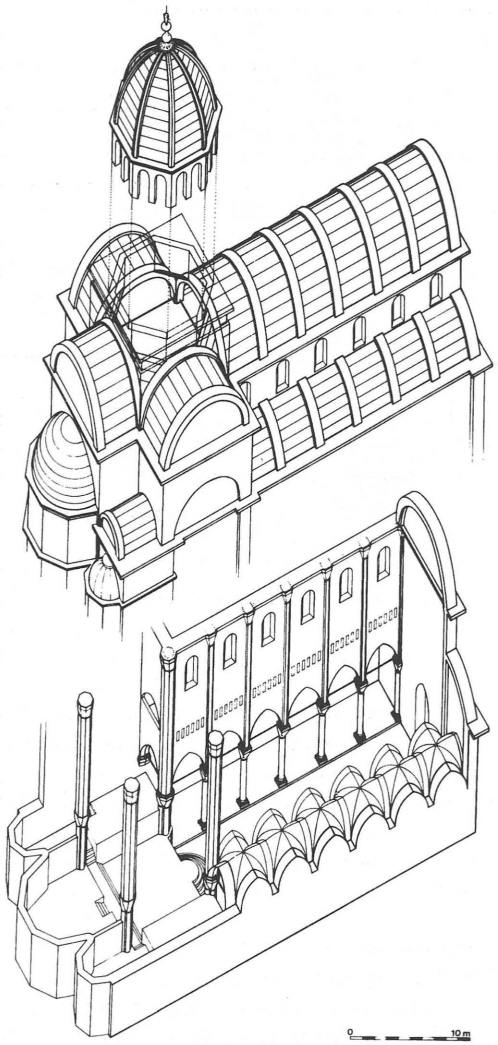

Figure 1
The unique structure of the cathedral of Šibenik

Construction

The citizens of the small Dalmatian town of Šibenik, on the Croatian Adriatic coast, decided to build a new cathedral at the beginning of the 15th century, in a difficult period of dynastic wars between Ladislaus d'Anjou and Sigismund von Luxemburg. After Ladislaus d'Anjou sold Dalmatia to Venice, Šibenik resisted the Venetian siege for three years and then was forced to surrender. In spite of the new threatening force —the Ottoman empire (the border of which was not more than a few kilometres away from the town of Šibenik at the end of the 15th century) (Grubišić 1974, 34–65), in 1431 the citizens of Šibenik began the building of their cathedral (Fosco 1893, 61).

The construction was started probably after the design of the Lombard master Bonino da Milano (Stošić 1950, 130). Although Bonino died in 1429, i.e. two years before the construction started (Kolendiæ 1924b, 467), he is probably the author of the first project of the Cathedral, as in a document from ca 1430 he is mentioned as «primus magister ecclesie nove sancti Jacobi» (Stošić 1950, 130).

After «Franciscus quondam Jacobi de Venetiis» (Francesco di Jacopo da Venezia), who was in charge of the construction for one year only (1431), the cathedral did not have a protomagister at all. The construction was carried out by two unexceptional Venetian masters, Antonio Busato and Lorenzo Pincino (Kolendiæ 1924a, 174) who began to build the perimetral walls of the western part of the cathedral. They constructed at least the western part of the northern façade and northern part of the western façade up to the height of the Lombard frieze, which should have been the upper cornice of the northern wall of the aisle. Lorenzo Pincino was in charge of the construction also of the first bay of the northern aisle. (Frey 1913, 129–130.)

Then, in 1441, a sudden break of construction: the document of the City Council mentions «multi errores et defectus» (many mistakes and flaws), which caused «magnae expensae . . . quoniam aedificia et partimenta ipsius Ecclesiae non fuerunt dibitis modis composita et fabricata . . . » (Fosco 1891, 9). In such critical moment the citizens of Šibenik decided to employ a new, skilful and well-trained protomagister: they invited from Venice, a flourishing political and artistic capital, master «Georgius quondam Mathei de Jadra habitator Venetiarum» who called himself Dalmaticus (Fosco 1891, 10–11; Frey 1913, 131–132). Indeed, Georgius Mathei was by origin from Zadar («de Jadra»), another Dalmatian town not far away from Šibenik. He obviously solved successfully the serious structural problem mentioned in the document from 1441, and in 1443 he began with the construction of

the eastern part of the church —in a radically new way of building. While the walls of the western part of the Cathedral, built before, are constructed of ashlar (stone blocks masonry), the apsidal part is built using specific technique of assembling large stone slabs into the stone «frames» (Ivančević 1997, 29). Georgius Dalmaticus (George the Dalmatian) changed also the spatial concept of the church, extending it into east and introducing **a** transept crowned with **a** dome. He also worked in the interior, constructing aisles and **the** nave wall up to the frieze of leaves (Montani 1967, 16–17).

«Nicolaus Johannis florentinus» (Nicholas the Florentine), protomagister who conducted the construction of the Šibenik cathedral 1477–1505 (Fosco 1891, 25–26; Frey 1913, 40, 164), adopted the specific constructional method of the apsidal part and applied it to the barrel and semi-barrel vaults of the church, and even to its dome. Thus he created an original vaulting system, assembling large elements, cut of the high-quality stone.

The following protomagistri of the Šibenik cathedral, «Bartolomeus quon. magistri Jacobi de Mestre» (Bartolomeo di Jacopo from Mestre), and later on his son Jacopo (Frey 1913, 44), completed the cathedral (the upper vaults of the aisles and nave) by using the same form (semicircular barrel vault for the nave and semi-barrel, less-then-a-quarter-circle vaults for the aisles) and the same constructive and structural system. In 1536 the construction of cathedral was completed by putting the key-stone on the western trefoil façade and simultaneously the «key-slab» of the first western bay of the nave vault (Fosco 1893, 61).

THE UNIQUE CONSTRUCTIVE AND STRUCTURAL SYSTEM OF THE UPPER VAULTS

Unique way of construction

The unique upper stone vaults of the cathedral of Šibenik are constructed in the original way: their webs are assembled of large thin monolithic slabs (their spans vary from 3.00 to 4.20 m, while their thickness varies from 15 cm to 25 cm —due to roof-tile-like overlapping). These stone slabs are wedged into slender stone arches, monolithic in cross-section (80 cm wide, 55 cm high in cross-section), which span 7.75 m (Šimunić 1989).

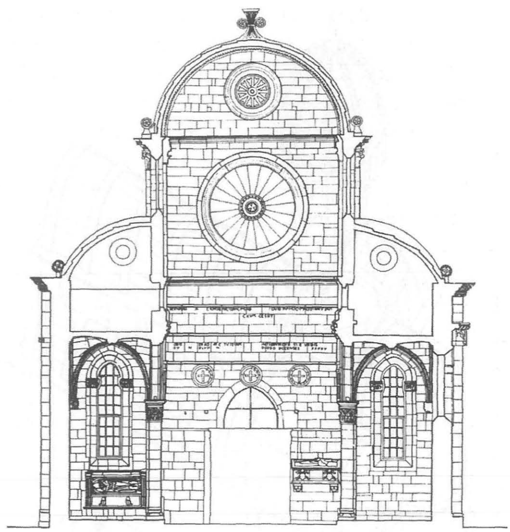

Figure 2
The cross-section through the nave and the aisles of the cathedral

The principle of assembling, applied also in the construction of the walls of the apsidal part of the Cathedral (where the large thin stone slabs are fixed into stone «frames» —vertical and horizontal stone bars— was probably inspired by timber constructions. Indeed, not only had many churches in Venice wooden vaults «a carena di nave» (Ivančević 1985, 29), but also other cities in Northern Italy (Verona, Aquileia . . .) as well. It seems that also the ancient cathedral of St Anastasia in Zadar, native town of Georgius Dalmaticus, had a wooden vault «a carena di nave» (Petricioli 1983, 62–63).

The method of building in one material (wood) was «translated» into the constructing in another material (stone), with essentially different characteristics —in an ingenious, outstanding way. Wood is a traditional material that is able to assume both compressive and tensile stresses. Therefore it has been used for millennia for flat floor structures, where bending occurs, i.e. both compressive and tensile stresses appear.

On the other hand, stone is extremely resistant to compressive stresses, while its tensile strength is much lower. Therefore, when used for covering spaces, it was applied as massive masonry vaults,

which had a shape adjusted to the pressure line, in order to avoid tensile stress. Masonry structures have even lower tensile strength than stone as a material, because the joints between stone elements (usually mortar) have a negligible tensile strength (Di Pasquale 1984).

The way in which the constructors of the cathedral of Šibenik used stone for building vaults is unique. In fact, the method of erecting the vaults of the Cathedral had been a mystery —until the recent disassembling of the dome, damaged during the war in 1991. It was impossible to be sure how the details of the vaults were actually made, although the vaults were visible from the interior and the exterior (since they have never been roofed). Many art-historians (e.g. Josef Durm - 19th-20th century) assumed that the vault rib elements were made of two parts tightened together.

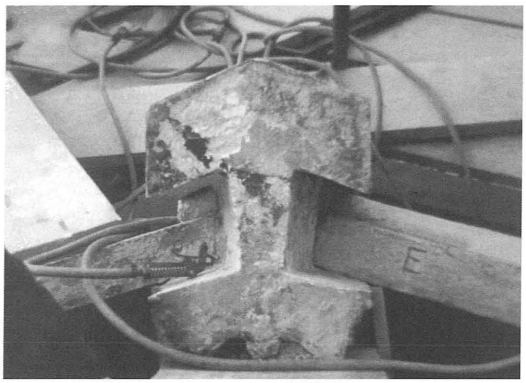

Figure 3
Dome rib during disassembling (photograph by M. Škugor)

Only ten years ago, during the partial disassembling of the dome, precise and original constructional details were rediscovered Surprisingly, the arches of the dome are monolithic in cross section, with grooves in which the precisely cut slabs are fixed. Because of the intricate spatial geometry of the dome, stone wedges (lateral and frontal) were put into the arch grooves, to fix the slabs tightly and precisely (Škugor 1997, 138–139).

In order to reassemble the dome correctly, during the reconstruction a real-scale model of the dome was made, for experimental purposes (Kostov 1997, 134–135). It showed how the dome had been built: in horizontal rings, with slab layers and arch elements shifted by ca half a height. It was proved that the dome was stable at any stage of the construction, and that it could have been erected without scaffolding. In fact, every horizontal ring, when closed, is assured against overturning, and elements of the existing ring, (e.g. arch elements) stretching upwards, provide secure support for the elements (e.g. slabs) of the next horizontal layer (Škugor 1997, 139).

This ingenious structure with its precise details proves that in the time of Renaissance Dalmatia had high-skilled stonecutters, able to realise original, daring, new structural concept of the creators of the cathedral.

Unique structural behaviour

The unique stone vaults of the cathedral of Šibenik, assembled of thin large monolithic slabs, wedged into slender stone vaults, are much lighter than usual massive barrel vaults. And, what is even more important, unlike masonry barrel vaults, they transfer their load mostly in the longitudinal direction, to the arches, as the computational analysis proved. (Šimunić 1989, 84–93).

Thus, the vault loads —and consequently their horizontal thrusts— are concentrated onto a limited number of points —the supports of the arches. As the arches are tightened with iron tie-rods, their horizontal thrust does not affect their slender substructure (Šimunić 1989, 185).

In contrast to this, the usual massive masonry barrel vaults load their substructure with considerable horizontal forces along the whole length of the walls —which is a very unfavourable influence on their masonry substructure.

STRUCTURAL BEHAVIOUR OF THE ŠIBENIK CATHEDRAL DURING CONSTRUCTION

Method of research

In order to understand the construction history of the cathedral of Šibenik from the structural point of view, we explored the mechanical behaviour of its structure in several building phases. On the basis of the

historical sources (previously analysed by numerous art-historians who researched documents from the time of construction, preserved in the Šibenik archives, as well as other historical sources —e.g. coats of arms, incised in the walls of the cathedral), we tried to establish up to which extension and height the Cathedral was built in several crucial periods.

While art-historians concentrated on attributing several parts and elements of the Cathedral (especially sculptures) to certain authors, we considered the Cathedral as a building, the structure being its essential feature.

We built 3D models of the whole structure in order to check if the assumptions made by art-historians (established mostly through the analysis of stylistic details) can stand the examination of the structural logic of the building as a whole.

Then we analysed the mechanical response of the structure in several building phases that we had established. We used the experimental finite element method programme CALPA developed in the early nineties at the University of Florence for the analysis of masonry structures (Smars 1992). This programme is based on the theory of masonry mechanics developed by Prof. Dr. S. Di Pasquale (Di Pasquale 1984): low tensile strength of masonry is presumed negligible, and regions where tensile stress would appear are considered deactivated, fractured. Thus, the real, resisting structure is reduced (Di Pasquale 1992, 175), and the programme iterates calculations with a new stiffness matrix (Smars 1992).

Due to the limited possibilities of the programme used (only 2D analysis, limited number of finite elements), we analysed a characteristic cross section through the nave and aisles, actually through their primary structural elements —vault arches, pilasters and columns.

Thus, at least the northern part of the western façade and the western part of the northern façade were also built up to this height. The Gothic Lombard frieze (blind arches cornice) was also begun in this period, but it was probably not built in its full length. The art-historians have proved that the northern portal of the church, known as «porta dei leoni», begun before 1434 (Frey 1913, 8), was completed only in 1453–1454 (Folnesics 1914, 47). As the ninth bay of the northern façade has decorative elements belonging to a later period, and as it is built in another way, completely different from the usual ashlar masonry, applied in the firstly built parts of the church, it is certain that the eighth bay of the northern façade is the ultimate limit to which the first builders —Francesco di Giacomo in the first year, and Antonio Busato and Lorenzo Pincino later on— could have carried out the construction.

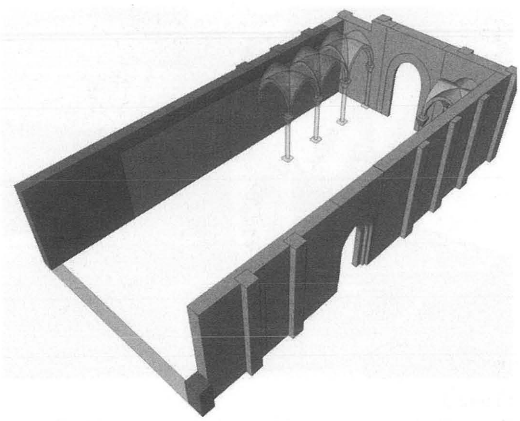

Figure 4
The cathedral of Šibenik —construction completed by 1441

Structure completed by 1441

First, we analysed the structure as it was presumably completed by 1441, when serious structural problems appeared. From the documents and coats of arms incised on the walls, it is certain that at least the northern pilaster of the western façade was completed up to the height of the Lombard frieze (Frey 1913, 7), which should have been the upper cornice of the building.

Documents testify that in this period also at least one bay of the northern aisle vault was completed: its first western bay. It is vaulted with a usual Gothic ribbed groin vault. As the lower part of the northern façade (outer wall of the northern aisle) has a row of pilasters, which do not exist in its upper part, we assumed that the first constructors of the Cathedral built these pilasters as shallow buttresses intended to assume the horizontal thrust of groin vaults.

Therefore, we supposed that the structure was

originally designed as Gothic vaulted structure, buttressed by façade pilasters, i.e. without iron ties, which are present in the structure now.

The computational analysis of a 2D model of such structure, built up to the groin vault and the Lombard frieze, showed that even at that early stage of construction serious structural problems would have appeared if the structure had not have additional elements for assuming the thrust of the groin vaults. In fact, the pilasters proved to be insufficient for that purpose, because tensile stress in the vault and its diaphragm would have appeared, causing significant relative displacements of the nave wall and aisle façade. The large continuous fractured region in the midspan of groin vault arch and in its diaphragm would have caused **a** discontinuity in the structure.

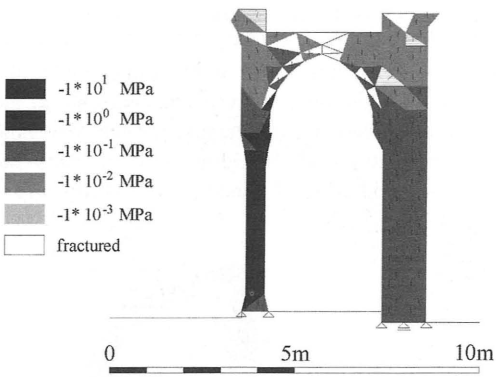

Figure 5
Compressive stresses in the structure completed by 1441

This would have transformed the more stable two-support (two-wall) structure, connected with a vault, into two independent vertical cantilevers —much less stable against horizontal forces.

But even if such a structure was loaded only with dead vertical loads, the cracks and significant relative horizontal displacements could have caused significant damages, and **a** fractured vault would have been a warning. This state of stresses and displacement could have caused even a real collapse of the vault bays, constructed until 1441.

This consideration inspired us to formulate a new hypothesis of the possible «errores et defectus» which caused the suspension of construction and urgent invitation of a new, experienced protomagister. Until now, the art-historians assumed that these mistakes occurred in the apsidal part of the building (Frey 1913, 16), because it was the first part to be built by the new protomagister, Georgius Dalmaticus (even though the construction of the eastern part began only in 1443).

This hypothesis can be confirmed with the fact that all the capitals of the nave arcades and all the wall capitals of the aisle walls of the groin vaults have the stylistic characteristics of the first (Gothic) period —all but the third capital of the southern nave arcade and the first wall capital of the southern aisle wall (Frey 1913, 12).

Therefore, it seems plausible that the damage occurred in the southern part of the building. Indeed, the Cathedral is built on the steep slope, and while its northern side was founded on the rock, its southern side was founded on a less rigid support. Moreover, the episcopal palace is leaned on the southern wall of the Cathedral, and acts as a buttress, while the first three bays of the southern aisle do not have such «buttressing system».

Knowing this, we formulated the hypothesis that the damage, mentioned in historic documents, occurred exactly here. Thus, the structural analysis of the Cathedral in the first construction phase, when serious damage occurred, inspired a new hypothesis on the nature of that damage. To control our hypothesis, we analysed also the building in the next phase.

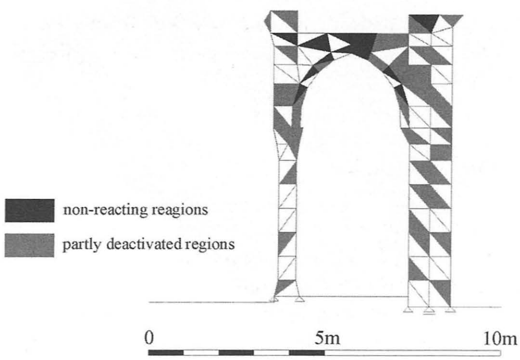

Figure 6
Critical regions in the structure completed by 1441

Construction completed by protomagister Georgius Dalmaticus

Protomagister Georgius Mathei Dalmaticus obviously solved the construction problem (whatever it was —the cracks in the vaults, due to insufficient thrust-assuming system, or any other problem) and built the eastern part of the church using specific assembling method, unusual in stone construction. (Ivančević 1997, 29). It is certain that he used iron ties for assuming the horizontal thrust of the groin vaults, and that he completed these vaults following the model of the first northern aisle bay, built by Pincino. According to our hypothesis, he adopted the same shape for the new vault bays, but he changed the structural system of the vault, introducing iron ties to prevent the structural problems that had already endangered the structure. There are no proofs that the first builders of the Cathedral did not use the tie-rods. However, there are proofs that Georgius Mathei did use them. In the contract for building the sacristy adjoining the Cathedral, they are explicitly mentioned: «duas catenas ferreas largas . . . pro archivolto dicte Sacristie» (Frey 1913, 153).

Construction completed up to the semi-barrel vault of the aisle

To research the structural behaviour of the structure in the next stage of construction, we analysed the structure when also the upper vaults of the aisles were built. First bays of these vaults, next to the dome, were built probably before the construction of the dome, i.e. before 1499, under the protomagister Nicolaus Florentinus.

The thin semi-barrel vaults and their slender substructure testify that the architect built-in iron ties, as we can still see. The part of the northern façade (northern aisle wall) above the Lombard frieze does not have pilasters —the façade surface is plain. It proves that the architect did not rely at all on pilasters as buttressing elements, that he entrusted the role of assuming horizontal thrust completely to the iron ties. This solution was successful, for no structural problems have ever been mentioned since 1441.

The computational analysis of the structure in this phase of construction confirmed the historical data. In spite of bigger height and consequently bigger dead load, in spite of another vault, placed higher in the structure, which therefore could have influenced the vertical substructure even more unfavourably, the state of stress is much more convenient than in the first analysed case. Due to the tie-rods, which assume almost the entire horizontal thrust of both vaults (the upper and the lower one), the vertical substructure is

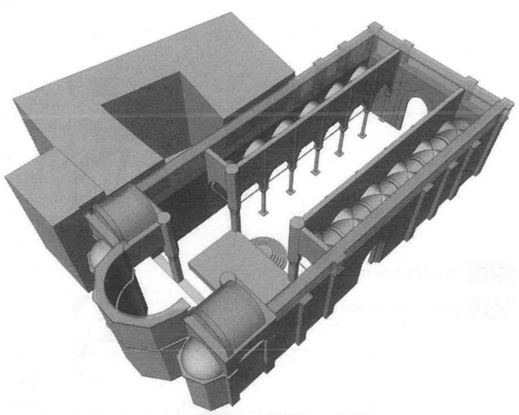

Figure 7
Construction completed by protomagister Georgius Dalmaticus

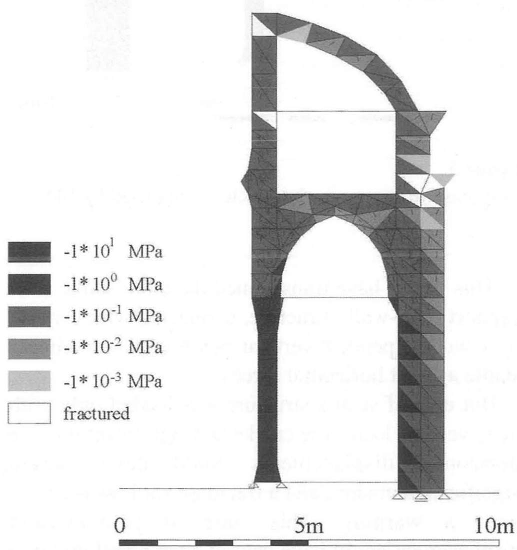

Figure 8
Compressive stresses in the structure completed up to the semi-barrel aisle vault

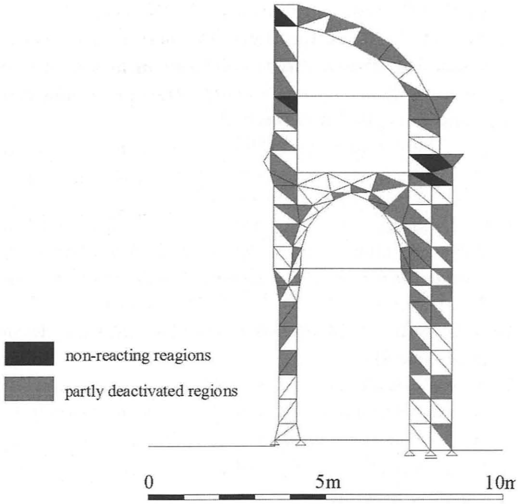

Figure 9
Critical regions in the structure completed up to the semi-barrel aisle vault

slender. Nevertheless, the critical, fractured areas are reduced to **a** minimum. There is no dangerous fractured region in the midspan of the groin vault and its diaphragm. Small deactivated areas appear due to the local influences, such as the concentrated force of the tie-rod, which causes fractures in a small area (a point, really) at the tie-rod anchoring. Another critical point is the support of the arch of the semi-barrel aisle vault on the nave wall —due to the vault thrust, which at that point is not assumed by a tie-rod, nor contrasted by a load of the nave vault above (not constructed yet, in this phase).

But these deactivated areas are neither large nor continuous; they do not occur at the vital points of the structure and do not spread through the whole section of structural elements. Therefore, they do not endanger the structure.

Conclusion

The history of architecture is the history of construction, the history of structural concepts and systems, rather than the history of decorative forms and stylistic conventions. Structure is an intrinsic component of architecture.

Throughout the history, traditional empirical knowledge of «res aedificatoria» (the art of building), based on direct observation of existing structures, allowed only slow, gradual changes of structural concepts. Therefore, the examples of radically new, original constructive and structural concepts, which broke with the tradition, are extremely rare. Of course, many «experimental» buildings have not survived the environmental forces and impacts.

The original, innovative structures that resisted all the impacts for centuries proved their structural qualities ipso facto. One of these outstanding buildings is the cathedral of Šibenik, with its unique vaults, constructed in the original way, which, consequently, results in the specific structural behaviour.

The static analysis of several construction phases, reconstructed on the basis of historic documents and previous art-historical researches, proved that the structure, which was presumably begun without tie-rods, with shallow pilasters as buttressing elements, was not resistant enough to withstand the horizontal thrust of the groin vaults of the aisles —not even in the first phase of building (1431–1441).

The creation of fractures in the bays of the groin vaults, erected until 1441, may well have caused the suspension of construction. Indeed, when the building was stopped due to «errores et defectus» which caused heavy damage «quoniam aedificia et partimenta non fuerunt dibitis modis composita et fabricata» (Frey 1913, 130), there must have been serious structural flaws that endangered the construction.

Because of that serious structural problem, a new protomagister was invited: Georgius Mathei Dalmaticus. He managed to correct the «errores et defectus», to remove weaknesses and to continue the building, using iron tie-rods. He also developed a new, original construction system, erecting the walls of the apsidal part of the Cathedral by assembling large stone slabs, fixing them into stone frames.

His successor, Nicolaus Florentinus, applied the principle of assembling large stone slabs to the construction of the upper vaults of the Cathedral. The thin monolithic slabs are fixed into the slender stone arches, which are tightened with iron ties. Thus, an original vaulting system was developed, which differs substantially from the usual masonry barrel vaults.

Therefore, no massive substructure or buttressing system is necessary.

Indeed, the analysis of the next stage of the construction, when also the upper, semi-barrel aisle vault was completed (and assuming that both vault arches are tightened with iron tie-rods), displays clearly that this system has no structural weaknesses. Due to local influences (tie-rod force, e.g.) only small localised fractured regions appear, which do not endanger the structure as a whole.

The strength of the Cathedral structure, daring and apparently fragile, was proved in 1991, when it resisted even a direct bombshell shot.

«Virtual experiments» on the structure of the Šibenik cathedral (some of which are described here) gave a new insight into its mechanical behaviour during the construction, and into the possible reasons of the structural failure in the beginning of its building. Like the ancient masters, who made use of this failure to develop a new constructive and structural system, contemporary architects and architectural historians should be aware of such episodes in the construction history in order to better understand how the historic structures were designed and constructed. Thus, we would be able to grasp the very essence of our architectural heritage: its structure.

ACKNOWLEDGEMENTS

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The role of geometry in the theories on vaulted structures by Lorenzo Mascheroni (1785)

Anna Sinopoli

From a viewpoint essentially oriented towards problems of strength of materials, modern Structural Mechanics considers the balance equations of Statics as fundamental in the formulation of the equilibrium problem.

During the course of history, however, scientific reflections and theories worked out with regard to «mechanical questions» were almost always characterised by their being focused mainly on the analysis of possible or real movements of the systems, or the geometric parameters that characterised them. This circumstance is perhaps connected with the fact that, before the introduction of abstract quantities and concepts through the use of mathematical language, «mechanical questions» were regarded as reflections concerning practical facts of an empirical nature, in the search for the natural law that governed the phenomenon. In particular, the problem of equilibrium has often been analyzed as the search for the «limit condition» at which a mobile system could be placed in a state of non-mobility.

It was this strong emphasis on the «not activated, but possible» mobility of the system which led to the main reference of the scientific theories worked out over the centuries, the so-called «Principle» of Virtual Works, being assumed as a natural law, or a fundamental postulate.

All the «objects» that have constituted the history of Mechanics are mechanisms; all these «objects» have in common the fact that they are mobile systems, for which the condition of equilibrium requires particular values of the forces applied —usually weights. For such systems, the formulation of the equilibrium through the equations of balance required that Statics be considered as a particular case of Dynamics.

On the other hand, once the concept of weight as a being that has the tendency (which is, moreover, empirically demonstrable) to move downwards and is, therefore, susceptible to movement, was accepted, it is not surprising that the guiding principle of scientific thought was PVW: the search for equilibrium as a condition of «non-activated motion» placed the emphasis on kinematic analysis of the system —and therefore on geometry— through the link with weights, in the search for a law in which the science of weights was governed by geometry. The discovery of the particular condition of «non-activated» motion, that separates equilibrium from motion —or, in static terms, from collapse— coincides with what we nowadays call «limit analysis».

It is in this context that some theories of vaulted structures from Leonardo to La Hire were discussed and re-examined in a previous paper (Sinopoli 2002), in the search for an interpretation that was as close as possible to the thought of the time, while not excluding the use of modern formal instruments to enable an easier and more correct reading. It is along the same lines that the analysis and theories on

vaulted structures proposed by Lorenzo Mascheroni in his «Nuove ricerche sull'equilibrio delle volte» (1785) will be discussed and re-examined in this paper. It is with Mascheroni, in fact, that the analysis proposed by La Hire finds its justification, and arch collapse is examined by means of a mature formulation, based on kinematic analysis of the system.

THE ROLE OF MECHANICS AND STATICS IN SOLVING PROBLEMS REGARDING ARCHES AND VAULTS

As a confirmation of the fact that «mechanical questions» were for a long time considered as theoretical reflections on practical questions of a basically empirical kind, in the preface to «Nuove ricerche sull'equilibrio delle volte» (Mascheroni 1785), Mascheroni affirms that both Statics and Mechanics:

> . . . sono arti dirette all'uso, e la complicazione delle molteplici circostanze, che alterando lo stato della questione fanno che la sola speculazione riesca a decisioni lontanissime dall'esperienza, facilmente si vede dovere la teorica aver predominio nella Statica; siccome per lo contrario dovere la pratica essere consultata a preferenza nella Meccanica. Questa seconda (la Meccanica) procurando il moto trova gli intoppi nelle resistenze dei mezzi, nelle asprezze delle superfici, nelle tenacità, ed attrazioni varie delle materie, il qual genere di circostanze non è così facile di perfettamente rilevare per via di principj, e molto meno di assoggettare alla precisione del calcolo. Ma dovendosi pure ad esse avere tutto il riguardo da chi desidera conseguire l'effetto dei suoi tentativi, quindi è avvenuto che Geometri anche sommi hanno fatto precedere diligentissime e per più capi diversificate prove di fatto, dalle quali raccoglier potessero qualche legge da tenersi poi nel luogo d'un principio nella risoluzione de' Problemi. (Mascheroni 1785, XXIV).[1]

According to Mascheroni, therefore, Mechanics, considered as a science of motion, cannot be subjected to theoretical analyses due to resistance by the media and all the phenomena which are not controllable, but above all, with regard to such phenomena there are no principles to which reference can be made. Nevertheless, precisely because it is science of motion, it is in the geometry of movements that analyses and factual proof can be obtained; that is, theorems concerning kinematics, to be considered as principles in the solution of problems. However, it is the next observation that becomes a key to the interpretation of the role of Geometry in Mechanics and therefore also in Statics. In fact, Mascheroni continues thus:

> Al contrario la Statica cercando di introdurre in varj aggregati di corpi equilibrio e quiete trova ajuto al suo scopo in quelle medesime cose che contrastano colla Meccanica; sicché qualora essa abbia colla scorta della Geometria trovato il sito, e la distribuzione di quelle materie, che deggion star ferme, non può per conto delle circostanze annoverate di sopra se non istarsene più sicura. (Mascheroni 1785, XXV)[2]

Statics, which is concerned not with movement but with a search for conditions of equilibrium and rest, can take advantage of a geometric-type analysis of the position and mobility of the system —an analysis, therefore, of incipient motion or virtual analysis, as we would now say— searching for the conditions that prevent such a motion: equilibrium is obtained from non-activated or blocked motion.

> Quindi è che non deve sembrare che operi fuor di proposito, chi della fermezza degli archi e delle cupole si mette a trattare in una maniera quasi semplicemente teorica. Posto che un arco o una volta di qualsivoglia genere, costrutta sia in guisa, che per la sua figura e forma, attese le leggi di gravità, le varie parti delle materie che la compongono aver debbano fra loro equilibrio, per parte degli sfregamenti e delle malte sarà tanto più allontanato il pericolo della caduta. (Mascheroni 1785, XXV).[3]

Furthermore, the analysis is finalised to the search of conditions which will keep the danger of collapse at bay: limit analysis, therefore, through the Principle of Virtual Works.

But what was the state of the art as Mascheroni knew it? He criticises the author of the *Vite de' più celebri Architetti*, who, while agreeing with Frezer's recommendation that workers should not put their trust in practice alone[4], did not keep to this very theory that he recommended, but provided defective rules for the size of arches, vaults and cupolas, rules which were very remote from those that «Geometri di chiarissima fama di qua e di là dall'Alpi . . . hanno insegnato.» (Mascheroni 1785, XXVII).[5]

The names and writings of these Geometricians are quoted in the preface to Abbot Bossut's *Memoria* published in the volume of the Paris Academy in 1774. Two years later Bossut deduced the general equation for the equilibrium of domes; subsequently Lorgna

published a new theory on curves found in vaults in the Petersburg Commentaries (1779); on the same subject he also resolved many elegant and useful problems in his «Saggi di Meccanica e Statica», printed in Verona in 1782. As Mascheroni says: «pieno di rispetto per questi illustri scrittori che mi hanno preceduto ed istruito, io rifletteva non ostante che molte cose ancora restavano da ricercare.» (Mascheroni 1785, XXVIII) [6]

The open questions to which Mascheroni refers are aspects regarding the correct geometrical and mechanical description of the problems:

> Nissuno di loro aveva insegnato la maniera di far passare la curva dell'equilibrio per i centri di gravità degli elementi di un arco solido, maniera per altro la più diretta e naturale per ottenere la total sicurezza dell'arco medesimo . . . Tutti avevano posto questa curva nella concavità interna dell'arco, che intrados da' Francesi si suole con proprio vocabolo nominare. Essi non han fatto avvertire il pericolo della caduta dell'arco, che con un tale metodo di procedere molte volte s'incorre; molto meno determinarono quelle curve, che non lasciano mai l'arco esposto a simil pericolo . . . Trattò M. Couplet (Couplet 1731, 1732) la materia delle Volte piane, che piattabande si chiamano; ma non ne diede una teoria generale, e nello stesso caso particolare nel quale si impiega il cerchio per determinare le convergenze de' tagli delle pietre, non fissò alcun limite alla lunghezza delle piattabande, dal che ne segue manifesto rischio di rovina . . . Ma quello che più richiedeva l'esame geometrico si erano gli archi e le volte composte. (Mascheroni 1785, XXVIII–XXXI) [7]

We shall now proceed to dedicate our attention to the methodology proposed by Mascheroni for carrying out geometric examinations of arches. This process, based on axioms and hypotheses for the analysis of simple problems, evolves until it reaches the analysis and solution of Problems X and XI, the first formally correct example of limit analysis in the history of Mechanics. A cardinal point of this process is his geometric analysis of mobility, which reveals a complete knowledge of the characteristics of the act of motion of a rigid body.

The geometric principles of Mechanics and Statics in Mascheroni

On the equilibrium of Straight lines

Since Mathematicians consider curves as polygons with an infinite number of sides, before dealing with the curves which are required for the equilibrium of Vaults, Mascheroni first states some Problems on the Equilibrium of Straight lines. Such Problems, dealt with in part by Lorgna in his «Saggi di Meccanica e Statica» (Verona 1782), are taken up again not only to ensure complete treatment of the matter, but also to give new demonstrations of them. The problems are preceded by a few hypotheses which constitute the axiomatic premise of the analyses and theorems developed by Mascheroni.

The geometric-mechanical model: axioms and hypotheses

1) The motion under consideration is an infinitesimal movement of the first order: « . . . il moto è lungo una linea infinitesima, perché in tale ipotesi il moto segue con velocità uniforme per tutta la linea, il che è necessario per calcolare la quantità di moto. Inoltre, tale ipotesi è necessaria per ogni caso in cui il centro di gravità di un corpo muovendosi cambi continuamente direzione.» (Mascheroni 1785, 2).[8]
2) Relative gravity is that which pushes a body along an inclined plane. The product of such gravity for the mass is to be called relative weight.
3) Equilibrium is born from the equality of forces, understood as a product of the weights for the relative velocities (Principle of Virtual Velocities). In fact, « . . . si considererà il rapporto che possono avere tra loro due forze contrarie facendo seguire per supposizione il moto di due centri di gravità lungo due linee infinitesime da una parte e dall'altra; uno dei due moti è effetto dell'altro.» (Mascheroni 1785, 2).[9]

Theorem I or of the equilibrium of two weights connected by machine construction

Let two weights p_A e p_B be placed initially in A and B (Fig. 1). Consider the infinitesimal trajectory Aa of p_A upwards along an inclined plane and simultaneously, due to machine construction, the infinitesimal downwards trajectory Bb of p_B; if the motion occurs in the same interval of unitary time, Aa and Bb represent the virtual velocities of A and B. In addition,

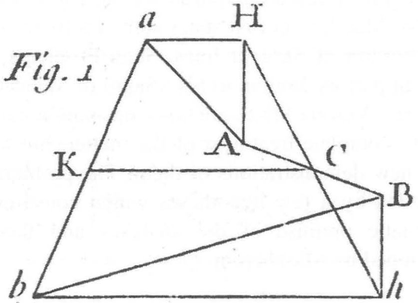

Figure 1
The equilibrium of two weights connected by machine construction

let *AH* and *Bh* be the vertical projections of the trajectories *Aa* and *Bb*. The equilibrium condition of the system requires that the products of the weights be equal for the corresponding vertical trajectories in the two opposite directions, and that is:

$$p_A\, AH = p_B\, Bh \qquad (1)$$

Theorem II or Torricelli's Theorem: If there is equilibrium, that is (1) holds, A and B's centre of gravity does not descend.

Theorem III or on the characteristics of a displacement of a rigid body: «Se una linea retta fa un moto infinitamente piccolo qualunque, tutti i punti di essa linea fanno un viaggio eguale sulla direzione della medesima linea.» (Mascheroni 1785, 4–5).[10]

Si consideri l'asta *QM* che, per effetto di uno spostamento infinitesimo, si porta in qm. Abbassata dalla posizione variata di ogni punto la perpendicolare a *QM*, e individuato lungo l'asta il punto H caratterizzato soltanto da uno spostamento parallelo alla configurazione iniziale *QM*, si afferma che: *Hg* = *He*, *Hq* = *Ha* e quindi: *gq* = *ea*, Figure 2. Puoi per caso esprimerti meglio in italiano?

Consider the rod *QM* which, as a result of an infinitesimal displacement, moves to qm. Having lowered the perpendicular segment to *QM* from the varied position of each point, and having identified point H along the rod —this point being characterised only by a movement parallel to the initial configuration *QM* – one can affirm that: *Hg* = *He*, *Hq* = *Ha* and therefore: *gq* = *ea*, Figure 2.

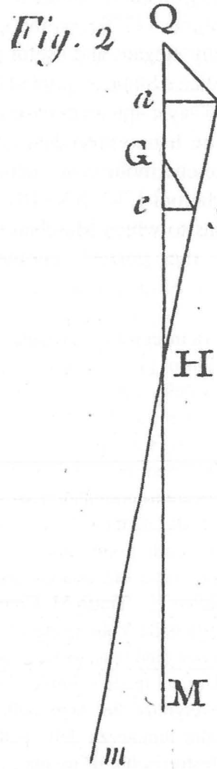

Figure 2
The characteristics of the infinitesimal displacement of a rigid rod

As has already been said, this implies that the movement of each point is an infinitesimal of the first order. In addition, the movement of each point can be considered as a vectorial sum of a constant displacement, along the direction that coincides with the initial rectilinear configuration (the translational component of the motion equal to that of the chosen pole) and of a displacement that is orthogonal to the direction, coinciding with the initial rectilinear configuration (the component of the motion due to rotation around the chosen pole).

Although this has not been demonstrated, the essential features of an infinitesimal displacement of a rigid body are fixed for the particular case in which a point *H* of the rod moves in the direction *QM*

parallel to the rod itself: this movement, which is an infinitesimal of the first order, can be considered the sum of a contribution from the translation, equal to the movement of the pole H, and of a contribution from the rotation, orthogonal to the direction defined by H and the point under consideration.

PROBLEM I OR OF THE EQUILIBRIUM OF WEIGHTS AT THE EXTREMITIES OF ARTICULATED RODS

The system consists of due rigid rods CB and BA hinged in B. A weight in B moves as a result of the rotation of the rod CB around C, while a weight in A descends along a vertical trajectory. This is a first schematization of the collapse mechanism of a symmetric arch, with a formation of five hinges: one at the key extradox, two at the intradox of the rupture joints and two at the extradox of the springers. This simplified model ignores the weight of the rods and concentrates the weights at their extremities.

According to Theorem I, equilibrium requires that the product of the weight p_B in B, for its vertical upward trajectory pb, be equal to the product of the weight p_A in A for its vertical downward trajectory Aa, Figure 3:

$$p_B\, pb = p_A\, Aa \tag{2}$$

This demonstration, of a purely geometric kind, is based on the hypothesis that the displacement bB of B is orthogonal to CB (virtual displacement of a rigid body due to a rotation $\delta\theta_1$ around the pole C), so that:

$$pb = \mathrm{CE}\ \delta\theta_1 = CE\ pB\ /\ BE \tag{3}$$

The movement Aa of A is considered, on the other hand, to be the result of a vertical movement Vn due to the relative rotation of A around B, from which the vertical movement pb due to B must be subtracted, so that:

$$Vn = BF\ \delta\theta_2 = BF\ nA\ /\ AF = pB\ BF\ /\ AF \tag{4}$$

and:

$$Aa = Vn - pb = (BF\ /\ AF - CE\ /\ BE)\ pB \tag{5}$$

Thus, for equilibrium:

$$p_B\ CE\ /\ BE = p_A\ (BF\ /\ AF - CE\ /\ BE) \tag{6}$$

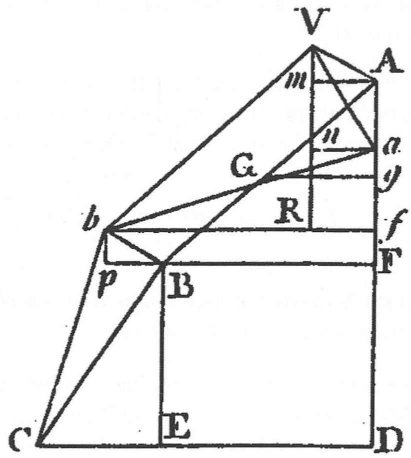

Figure 3

It is remarkable that the solution to this problem demonstrates a complete awareness of the fact that the absolute movement of A can be considered as an algebraic sum of the relative movement of A with regard to B, plus the movement due to the dragging of B.

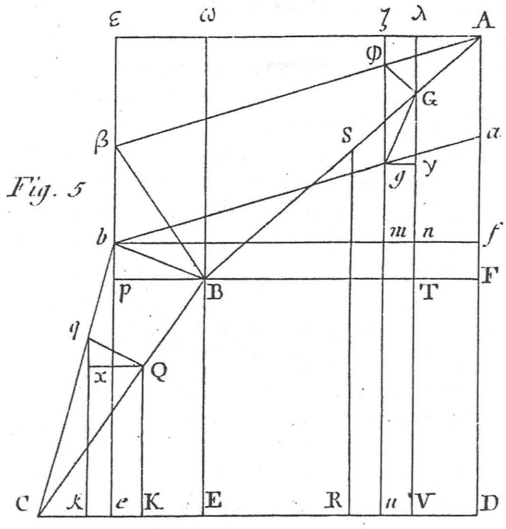

Figure 4

Problem II or of the equilibrium of heavy hinged rods

The demonstration is substantially similar to that of Problem I, only this time the weights are concentrated in the respective centres of gravity Q and G of the two rods. Thus, Figure 4:

$$p_Q\, CK / BE = p_G\, (BT / AF - CE / BE) \qquad (7)$$

Problem X or of the equilibrium of arches in the presence of infinite friction

On the basis of axioms, theorems I–II–III and the results supplied by the solutions to Problems I and II, Mascheroni was able to execute the limit analysis for Problems X and XI with coherence and rigour. Problem X is thus formulated as follows, Figure 5:

> Supposto che nell'arco solido LHAONVBM posto sopra le due basi LCRM, NSTO il punto A che si trova alla sommità possa discendere perpendicolarmente aprendosi l'arco in V, e lateralmente in H e P, e ascendendo i due punti B e X, restando sempre congiunte in un pezzo solo le parti HBVA, AVPX eguali, e parimenti le parti HLCRMB, XPOTSN, le quali debbano alzarsi col girare intorno a' due centri *C* e *T*, seguendo il tutto come se in C, B, A, X, T vi fossero delle cerniere; trovare la ragione delle due forze. (Mascheroni 1785, 28).[11]

Given the symmetry of the structure, the problem is analysed only for the semiarch. The solution, Figure 5, is obtained by using the same relationship obtained in Problem II. The limit situation of equilibrium therefore corresponds to:

$$p_Q\, CK / BE = p_G\, (BT / AF - CE / BE) \qquad (8)$$

Problem XI or of the equilibrium of arches with infinite friction at the springers and no friction at the rupture joints

This is the same collapse mechanism investigated by La Hire in 1712 and analysed again by Mascheroni according to the schema in Figure 6. The problem is formulated thus: «Supponendo che il pezzo di arco solido HBVXPAH (Figura 7) discenda perpendicolarmente, e parallelamente a sé stesso, e facendo cogli sdrucciolamenti de' lati HB, PX alzare i due pezzi HCRB, PTSX giranti intorno i centri *C* e *T*; trovare la ragione delle forze contrarie». (Mascheroni 1785, 29).[12]

Given the symmetry of the structure, the problem is once again analysed only for the semiarch. At collapse the keystone descends vertically, nonetheless maintaining contact at point *B* —the point of the rupture joint *HB*— with the lower voussoir rotating around *C*.

Since *bB* is orthogonal to *CB* according to Theorem III, from the solution of Problem II the vertical movements ba of point *B* and y_Q of the centre of mass *Q*, due to the infinitesimal rotation $\delta\theta_1$ of the springing voussoir around *C*, are respectively, Figure 7:

$$ba = CE\, \delta\theta_1 = CE\, Ba / BE \qquad (9)$$

$$y_Q = CK\, \delta\theta_1 = CK\, Ba / BE \qquad (10)$$

The vertical movement of all the keystone points, and therefore also of the centre of mass G, is considered to be an algebraic sum of a relative vertical downwards movement ea of G with regard to B, plus the upwards dragging movement ab of B. That is:

$$y_G = eb = ea - ab = Ba\, FN / BF - Ba\, CE / BE \qquad (11)$$

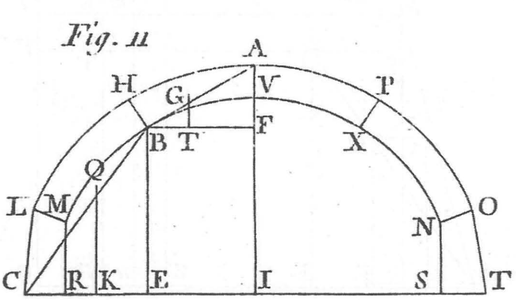

Figure 5

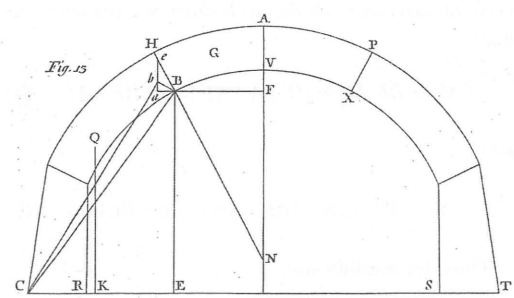

Figure 6

The limit condition for equilibrium therefore corresponds to:

$$p_Q \, CK \,/\, BE = p_G \, (FN \,/\, BF - CE \,/\, BE) \qquad (12)$$

It is interesting to compare the solution Mascheroni proposes with that previously proposed by La Hire. This too was based on Geometry: «On a crû qu'il falloit chercher dans la Géometrie une regle sur laquelle on a pût s'assûrer, pour determiner la force dont on doit faire les pieds-droits»[13] (La Hire 1712, 69).

With regard to Figure 7, to determine the limit condition for equilibrium La Hire takes the problem back to that of an equivalent simple machine, that is, of an angled lever with its fulcrum in *H*. The arms of this lever are *HT* and *HL*, at the extremities of which lie the weight of the abutment and the thrust *D*, respectively; the thrust *D* is orthogonal to *HL* and its role is equivalent to that of the weight p_G of the key wedge, which descends vertically, sliding without friction on the rupture joint *ML*. The crucial point is how to determine the thrust *D*. At this point La Hire states: « on sçait par la Mécanique que» (La Hire 1712, 72):[14]

$$LG : CG = p_G : D \qquad (13)$$

The proportion proposed by La Hire to calculate the thrust D appears to belong to consolidated knowledge —but what can the thought processes be that lead to consideration of the segments LG and CG?

It is only after having read Mascheroni that this proportion, so apparently obscure, can be justified. Above all, the axioms that Mascheroni establishes as fundamental to his theory consider it an acquired truth that, in a system made up of two weights joined by machine construction, equilibrium is guaranteed if the product of the weights —whether they are absolute or relative, that is in movement along vertical trajectories or inclined planes— for the corresponding virtual velocities is balanced. In fact, La Hire's problem seems to proceed from that of the two weights joined by machine construction: the first moves on an inclined plane corresponding to an upward movement *LG*, and has a relative weight *D*; the second weight p_G is that of the key voussoir which moves vertically, sliding along the rupture joint *ML*. The machine construction that links D's and p_G's movements is the condition for the maintenance of contact in L between the wedge and lower voussoir.

It is therefore surprising to discover that La Hire was well aware that while the weight *D* moves upwards along *LG*, the wedge maintaining contact in L makes a vertical movement that is the algebraic sum of the vertical downwards movement *EC* —the vertical relative movement of the voussoir with regard to *L*— and of the vertical upwards movement *GE* —dragging movement of *L*.

It would seem then that knowledge of geometry and in particular that of kinematic characteristics in the so-called mechanical questions was far more widespread and well-established than one would assume from the analysis of historical texts. Not only, but as asserted by Mascheroni in his preface to the Nuove ricerche sull'equilibrio delle volte (Mascheroni 1785), the role of Geometry understood as geometry of movement, was the real area of research in Mechanics, with the Principle of Virtual Velocities having been assumed as the unique principle of reference. It is with Mascheroni that this kind of geometric knowledge first acquires its systematic organisation of an axiomatic kind.

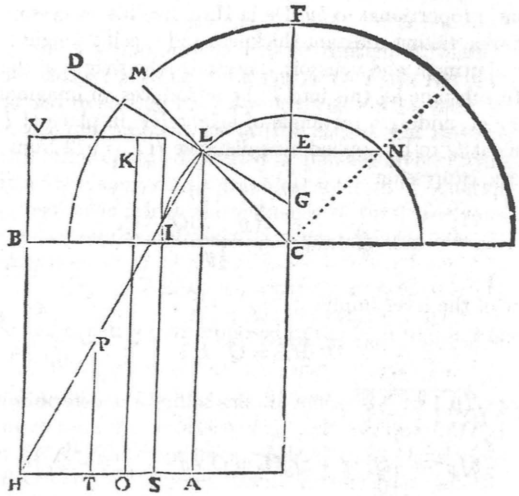

Figure 7
La Hire's collapse mechanism

Notes

1. « . . . are arts oriented to functions; the result of the complication of multiple circumstances that alter the status of the question is that only speculation succeeds in reaching decisions that are extremely removed from practical experience, and so it is easy to see that theory must predominate in Statics; contrariwise practice should be taken into consideration as far as Mechanics is concerned. This latter while engendering movement finds hindrances in the resistances of the means, in the roughness of surfaces, in the tenacity and various attractions of the materials. These kind of circumstances are not easily identified by means of principles, and even less can they be subjected to the precision of calculus. Nevertheless, as they must perforce be taken into account by anyone wishing to achieve results from his attempts, even distinguished Geometricians have first obtained detailed and diverse proofs with which they could subsequently formulate laws that could in some way substitute a principle in the resolution of Problems.»
2. «Statics, on the other hand, in its attempt to introduce equilibrium and quiet into various groups of bodies, is aided in its intent by the very things that contrast with Mechanics; so that whenever Mechanics, with the help of Geometry, has found its site and the distribution of those materials which should stay still, in the above-mentioned circumstances it cannot but be made even more secure.»
3. «It should not therefore appear that someone is working out of context when he treats the stability of arches and cupolas in an almost simply theoretical way. Given that an arch or cupola of any kind is built in such a way that by its shape and form, in accordance with the laws of gravity, the various parts of the materials that compose it must be in equilibrium with each other; and with the addition of friction and mortar the danger of collapse will be even further averted.»
4. «Even the longest practical experience is not sufficient for the correct building of Vaults. In this matter an old experienced man is an old ignorant man who can easily be mistaken even in small matters, the cases vary. In this particular matter there can be an infinity of cases in which the reasonings that a practical man may make after carrying out a work prove to be fallacious. Forty-six years of practice without theory could not teach the architect who, in a French border town in 1732, had to build a powder magazine —as he did not make the abutments of the correct thickness, the building collapsed before the scaffolding was removed.» (Autore delle *Vite de' più celebri Architetti*, 1768, part II, chap.1, Mascheroni 1785, XXVI)
5. « . . . extremely famous Geometricians from both south and north of the Alps . . . have taught us»
6. « . . . while fully respecting these illustrious writers who preceded and instructed me, I thought nonetheless that many things still remained to be discovered.»
7. «None of them had been taught how to make the curve of the equilibrium pass through the centres of gravity of the elements of a solid arch —a method which is also the most direct and natural for obtaining total security of the arch itself . . . All of them had placed this curve in the internal concavity of the arch, which the French call intrados. They had not warned of the danger of collapse of the arch, which with this procedure often occurs; even less did they calculate the curves that would never leave the arch exposed to such danger . . . M. Couplet dealt with the matter of plane Vaults, which are called platbands; but he did not provide a general theory about them, and in the particular case in which a circle is used to determine the convergence of the *cuts of stones*, he did not fix any limit to the length of the platbands, which leads to a clear risk of collapse . . . Above all it was the arches and composite vaults that required geometric examination.»
8. « . . . the motion is along an infinitesimal line, because according to this hypothesis motion occurs at a uniform velocity along all the line —this is necessary if one is to calculate the quantity of motion. In addition, this hypothesis is necessary for all cases in which the centre of gravity of a moving body constantly changes direction.»
9. « . . . we will consider the possible relationship between two opposite forces, under the supposition of making the motion of two centres of gravity follow along two infinitesimal lines on one side and the other; one of the two motions is the effect of the other.»
10. «If a straight line makes any kind of infinitely small movement, all the points on that line travel equally in the direction of the line itself.»
11. «Supposing that in the solid arch LHAONVBM placed above the two bases LCRM, NSTO the point A at the top can descend perpendicularly opening the arch in V, and laterally in H and P, with the two points B and X ascending (rising), the equal parts HBVA, AVPX remaining joined in one piece only, as also the parts HLCRMB, XPOTSN, which must rise as they turn around the two centres C and T, following everything as if there were hinges in C, B, A, X, T, find the ratio between the two forces.»
12. «Supposing that the piece of solid arch HBVXPAH (Figure 7) descends perpendicularly, and parallel to itself, and by the slipping of the sides HB and PX causing the two pieces HCRB, PTSX rotating around the centres C and T to rise, find the ratio between the opposing forces.»

13. «It was thought that one had to search for a rule in Geometry on which one could rely, to determine the strength with which the abutments should be made.»
14. «It is known from Mechanics that . . . .»

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Late XVII^th century practice of stereotomy prior to the establishment of Engineering Schools in France[1]

Randy S. Swanson

This paper explores the practice of French stereotomy in the late XVII^th century through the field study of the l'Observatoire de Paris, (1667–1672), designed by Dr. Claude Perrault (1613–88). This effort seeks to present modest evidence to the base line of performance in the practice of stereotomy prior to the establishment of engineering schools in France.[2] The l'Observatoire presents a unique case because substantial changes to the design of the Main Salon and Grand Escalier occurred after the construction was begun. It is suggested here that the detailed response to these changes offers a view of the empirical knowledge and capabilities that existed in that era. On-site research in Paris involving both field and archival efforts took place during the summers of 1997 and 1999.[3] The examination revealed a construction that was rationally systematized, generally of high precision, and employed a consistent patterning of joint-work to provide a significant contribution to the architectural effect of the project.

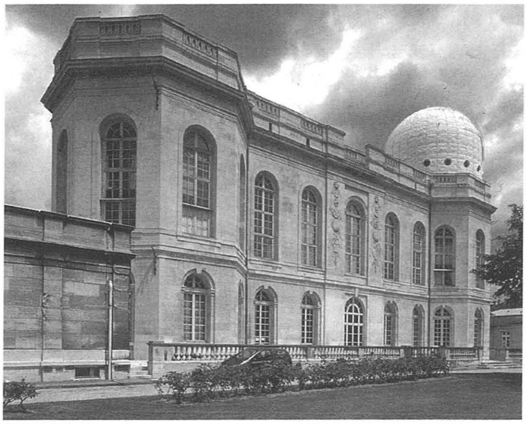
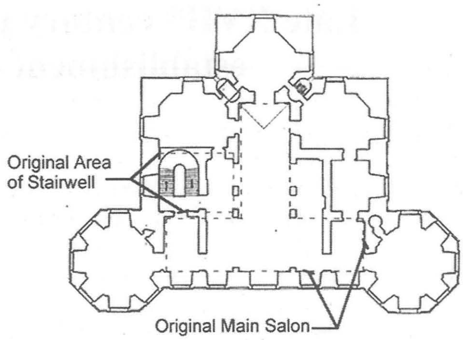


Figure 1

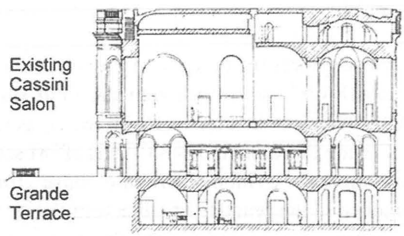
The establishment of the l'Observatoire represents a turning point for the development of modern science and this importance was appreciated by the members of the Academy from the outset. The l'Observatoire is a three story facility placed into the northern face of a small hillside that today, lies just to the south of the heart of Paris, Figure 1. The original intention of Jean Baptiste Colbert (1619–1683) Intendant of France, was to have a facility to house the core of all scientific activities in France. The new facility was expected to be the center for astronomical observations, provide a chemistry laboratory, permit the display of new inventions, mechanical models and machines, provide laboratories for anatomical dissections, as well as house the royal collections of natural history objects.[4] Permanent construction was employed to insure a consistent reference point for the measurement of astrological events over the next several centuries and to fix the location of the French prime meridian from which the most exacting measurements were to be made of Paris, France, and the earth.[5]

The pursuit of astronomy and geography became

the primary activities in this facility shortly after the arrival of Head Astronomer, M. Cassini (1625–1712), in the spring of 1669. Upon review of the design, Cassini argued before Louis XIVth, for a list of changes to insure that the l'Observatoire would serve as a perfect instrument. These included, the removal of a northern roof-access tower to have the night sky observable from any point of the roof; to change the octagonal towers to rectangular forms to ease observations; to insert a vertical solar observation port cut directly through the work that extended far below the foundations; the elimination of all reference to astrological symbols as ornamentation on the facade since they were non-scientific; and, to enlarge the main salon on the upper floor to accommodate academy meetings (Wolf 1902, 1–18. Dr. Perrault argued against the changes claiming the design was already perfect. Nearly all the changes requested were accommodated however. Of particular importance to this paper was the demand for a larger salon and its impact, Figure 2. The resulting «Cassini Salon» was a 15.5 meter wide clear span segmented vault replacing two intersecting cloistered vaults of 6.9 meters each. The increase of the salon also produced a fifty percent reduction of the area for a grand stair hall and a 90 degree shift of the stair. Climbing the same height in a reduced area required an increase in the slope of riser and tread and a corresponding need to reduce the width of the stairs resulting in a wonderful stereometric achievement of a cantilevered elliptically vaulted semi-helical stairwell.



Main Floor Plan w/Cassini Salon
Existing Conditions: Double vault w/Piers
1786 Renovation.



South-North Section
Base Drawings (1987) provided by permission
of M. Herve Baptiste, Architect en Chef
des Monuments Historiques, Paris.

Figure 2

General Construction

Before examining the grand escalier, it may be helpful to address the general state of the building construction. The facility is completely of stone. The work was supervised by Antoine Foucault of Saint-Marie and the quality of finish and jointing is consistently superior(Picon 1988, 212). Several construction strategies are revealed from a careful examination of the exterior northeast and south elevations.[6] The walling is of coursed ashler in a running bond of with a constant height within each course. Measurement of the wall coursing at grade level on the northeast elevation revealed that the first course above the watertable is 55.5 cm in height with all other coursing above this alternating between 44 and 41 cm. The exception to this is the course which contains the arch spring-line for the window apertures that has a height of 55 cm and corresponds to the spring-line of the interior vault. Coursing above this point returns to the smaller dimension of 44 and 41 cm. This technique where increased course heights are strategically located in the walling, was observed at the entry level of the southern elevation as well, where the common coursing height was modestly reduced (first floor of construction) and varies between 40 and 42 cm, with the more substantial coursing measuring 52 cm in height. The increased height of the coursing appears intentionally placed to provide greater resistance to the thrust of the interior vaults as well as stabilize the plane of the wall to restrain the thrust of the aperture arches.

At all apertures a round stepped arch construction can be observed. The purpose was to insure a maximum stability for the arch and wall. The method was more expensive than others because more surfaces had to be cut, but doing so prevented the slippage of stones over time. The transition of the arched window opening to the interior vault, as handled on the first floor, results in an intersection between two cylindrical surfaces and a visibly skewed ellipse. The masonry jointing in the soffit of the window vault demonstrates that the exterior and the interior stonework flow directly from one to the other. At the top of the salon vault is a keystone that interlocks the two salon vaults. Its surface is shaped as a «T», following the pattern of the vaults in plan. This shape, traditional to gothic masonry design and construction, is the geometrical resultant of dividing the vault surface with a series of radial lines to define the voussoirs for construction. An examination of the earliest detailed sectional drawing (dates from 1692+/-), reflects the heavy masonry construction of substantial wall thickness to restrain the vaults proposed for the facility. What is not reflected is that each room varies modestly so that it's likely that a vault would have been layed out directly on a newly constructed floor or wall to find the final dimensions. The result is remarkably harmonious effect of construction and a fluidity of space. The fundamental construction strategies of massed simple coursed construction,[7] interlocking prisms, and a continuity of construction geometry from exterior to interior constitutes the basis of the observatory construction.[8]

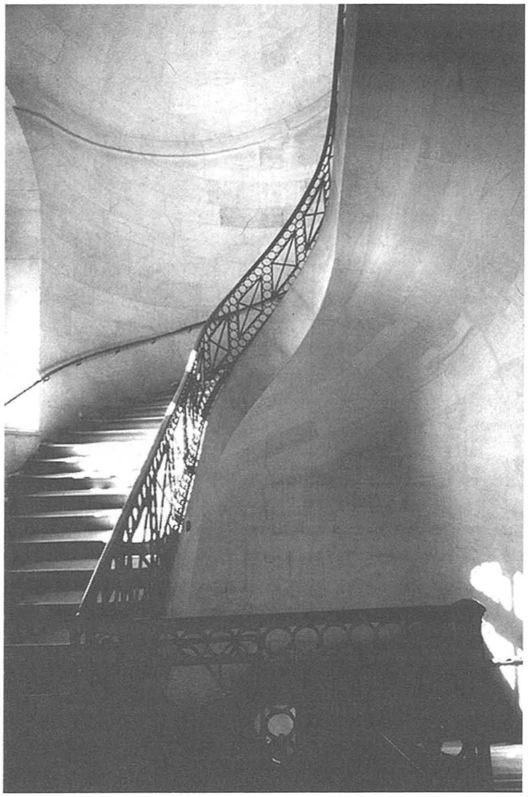


Figure 3

Grand Escalier Analysis:

Perrault clearly did not surrender his integrity under the impact of the changes forced upon his design, as the choice to replace the original semi-circular half-turn stair, was an *escalier a jour ou vis suspendu* (a suspended daylit elliptical stair), see Figure 3. This type of stair has been credited to Girard Desargues (1591–1662), the geometer, inventor, and architect, where is was installed at the l'Hotel de Ville de Lyon, in 1646 (Chaboud 1996).[9] This staircase appeared as a seamless plastic form defying gravity, an effect of growing fascination since Philibert de l'Orme invented the trompe de Montpellier at the Hotel Bullioud in 1536 (Potie 1996, 92–103). Desargues' influence seems limited however since his own projective methods appeared too complex and the illustrations of his work failed to provide convincing details of interlocking masonry construction.[10]

To convey the impact of this decision, Figure 4 presents two schematic sectional views of the semi-helicoidal stone stair hall. The total height of the stair-hall from the floor of the side entry to the rooftop terrace is 25.6 meters. This analysis is confined to the elements of the first floor vault-work at 4.96 meter elevation, and which occurs directly in line with the entry from the Grand Terrace on the south. A dimensional and unit/design analysis of the second floor suspended vaults of the stair-hall has been published elsewhere (Swanson 2002, 273–251). The piercing of the upper vault to permit the passage to the roof terrace offers an equally fascinating condition to examine, but presents a special case.

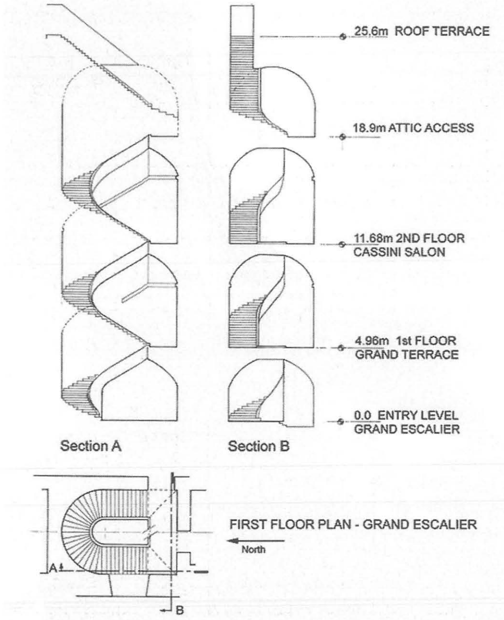


Figure 4

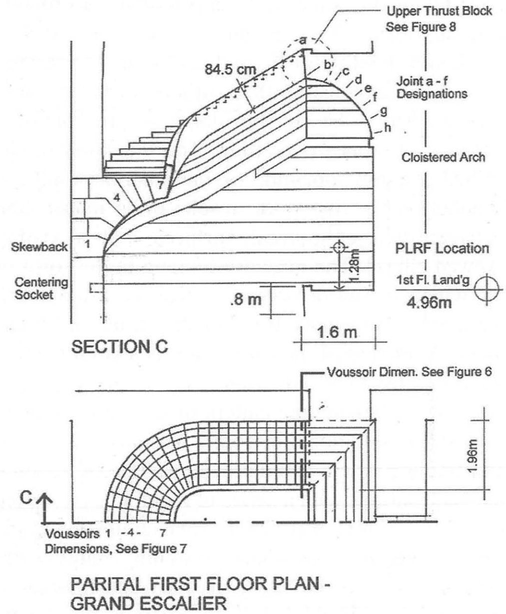


Figure 5

Figure 5, describes in parital plan and section the measured profile of the suspended horizontal groin vault of the landing and the inclined suspended vault of the rear stairwell. (To simplify further descriptions, the term 'suspended' will be understood when any vault of the stairwell is discussed.) The recorded field dimensions for both vaults are found in Tables 1 & 2. The profile of the vaults from the ground, first and second floors remain constant, given the minor variations of having been worked by hand. The concealed supporting structure of the vault presented the most curious portion of the problem overall. An insight as to how this may be constructed is provided by a close examination of the soffit for the interlocking voussoirs in the arched window openings. The internal jointing pattern and vertical dimensions of the voussoirs in section are an abduction by the author based upon the joint spacing in this portion of the stair-hall and the graphically determined thickness of the vault in section. The solution presented here, is suggested by visualizing a window arch as a section through the cantilever stairwell, which would result in producing interlocking prisms whose center's of gravity would fall behind the edge of the stone beneath it, thereby permitting each stone to be put in place without the workman's fear that it would fall from the vault. Of course, there is the added complexity that the stairwell is inclined and curving in three dimensions.[11] Such an approach however is not convincingly represented until Frezier's work nearly seventy years later (Frezier 1737, IV), or with certainty in the work of Rondolet. (Rondelet 1817, IV: Pl. LXIV). The quality of construction that this demands certainly falls within the exponential shift of increased precision that is being experienced in science in general, and particularly in surveying and astronomy.

It may be helpful to consider the face of the stringer conceptually as a soffit of an inclined splayed arch ring that has been rotated to a horizontal position to explain the stability of the inner ring of voussoirs 7, 6, and 5. That these prisms are acting in true arch form is suggested by the joint angle of each prism which is perpendicular to the angle of inclination of the vault, and not vertical to the horizon, which would require the insertion of iron cramps between the

Table 1

	Top of Stringer								Spring line	Horiz. distance
Point	a	b	c	d	e	f	g	h	j	k
Average ray length, in meters	un-view-able	5.74	5.86	5.91	5.96	5.97	5.96	5.92	5.64	4.78
PLRF angle of inclination	-	58.85°	55.34°	52.22°	48.35°	44.86°	41.14°	37.25°	33.08°	0.02°

Table 2

	Top of Stringer								Spring line	Horiz. distance
Point	a	b	c	d	e	f	g	h	j	k
Average ray length, in meters	5.10	5.07	5.37	5.62	5.82	6.11	6.34	6.50	6.57	6.55
PLRF angle of inclination	25.86°	16.36°	14.29°	12.20°	10.87°	7.82°	5.12°	1.89°	-2.14°	0.01°

prisms (Frezier 1737, III, 306–07).[12] While this is of modest conceptual help in understanding how the voussoirs of the stringer may work, it does not address the process of assembly since the complex warped stringer prism at mid-point can not act as a keystone.

It is suggested here that the assembly of the inclined vault probably proceeded in the following manner. Voussoirs 1–4, were put in place as the walling rose with the benefit of offering a narrow passage from level to level. The soffit joint pattern also suggests that these prisms were layed-up in a concentric ring in stair-step fashion. The landing and supporting horizontal vaulting could then put in place when that level of construction was reached. The remaining inclined vaulting, voussoirs 5–7, could then be cut and assembled with the certainty given the location of the lower and upper groined thrust blocks being in place.

In this approach, the keystone of the stringer would be the uppermost inclined block that abuts the upper groined thrust block since it would have been the last stone to be put in place. The upper groined thrust block ties constitutes the intersection of the three vaults and was probably too complex a prism to have been fitted into place last, see Figure 6. Support of this approach is provided by the presence of a square faced infill block at the rear wall of the stairwell, that coincides with the elevation of the landing floor, and probably fills a socket used to hold the centering for the completion of the vault assembly.

As the walling and vault merge into a formal system, a special concern was anticipated at the window aperture of the stairwell. At this point the continuity of that system was interrupted and required a special response to insure stability. At the window head, a transfer and a keystone prism —double the standard prism height, were put in place. The interlocking form of the keystone to insure a smooth transmission of upper vault forces can be viewed in Figure 7, where the joint patterns have been outlined. This is the only visible alteration of prism size within the design and from the minor fissures that have appeared directly above this point, where another window aperture for the second floor is located, the

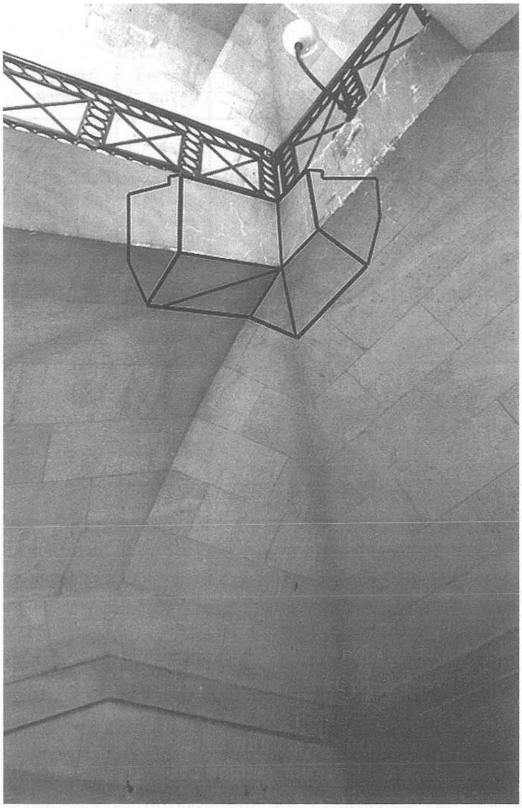


Figure 6

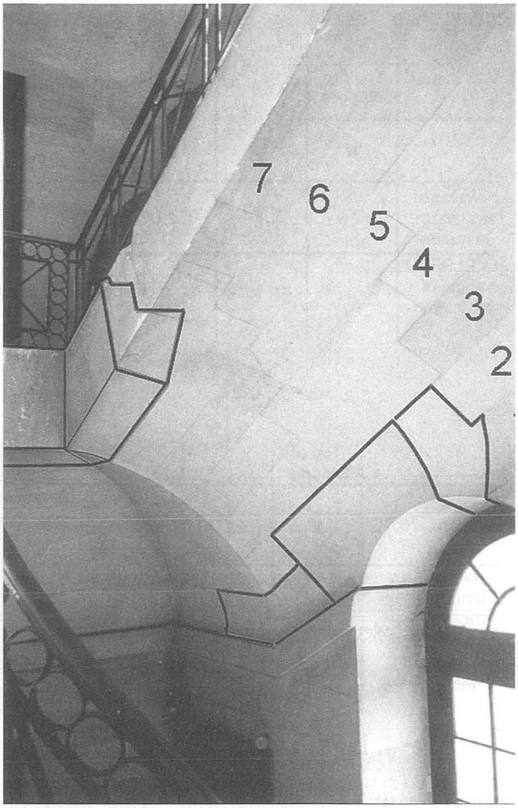


Figure 7

concern and response seems justified. For the sake of clarity, the voussoirs of the vault are also numbered in this figure, and the lower groined thrust block for the second floor vaulting is also outlined.

This notion of providing interlocking construction at points of concern can also be observed where the stair treads meet the sidewall. As the stairs run down from each landing, the treads interlock with the sidewall throughout the semi-circular rear wall to insure that all the surface work would remain fixed in place. The wall appears to have been cut after having been put in place since the joint dimension is substantially larger than elsewhere. In this manner the treads would have been placed last in the construction and although seemingly minor, and perhaps even an afterthought, the detail helps to reinforce that the method of assembly well thought-through.

The empirical and informed intuitive nature of the constructive/structural knowledge demonstrated in the stairwell is considerable and could be argued as systemic, where all the prisms rely upon one another to permit the successful resolution of the form. And it is not just in the stairwell where this was found, but also in the relationship between the interior vaults and the exterior wall construction. In this manner, the entire form, and by necessity the conceptual approach, has an organic sensibility that could be thought of as advanced Gothic design & construction.

The sense of craft, the fitting and finish of the stonework, speaks for itself. No where is this quality more evident than in the rear mid-point stringer prism with a complex warped surface. It is not just a geometric achievement but creates the impression of a sculptural effect throughout. The considerable

amount of stone that had to be removed to form this prism alone should not be lost on us. The sizing of this prism, and hence the sizing of the entire stairwell system presents a turning point for this discussion that must (somehow) address the presence of rules governing the execution of the project, or theoretical knowledge (Picon 1992, 11).

Two elements will be explored in the stair-hall, first the size of the stringer and then the inflection point at the intersection of the spiral and inclined arches. In this stair system three different cloistered vault types are connected, a half spiral, an inclined, and horizontal vaults.[13] The first floor landing width is 1.6m and the depth of the landing face is 80 cm, presenting the simple proportion of 2 to 1. At the inclined portion of the stringer, the dimension across the face of the stringer perpendicular to the angle of inclination is 84.5 cm and the width of the stair is 1.96 m. (see, Figure 5). The depth of the face is approximately equal to the inside radius of the stair in plan, (166 cm diameter/2 = 83 cm). When considered in section, minimizing the face dimension of voussoir #7 would seem to have been important. However, the elliptical profile of the vault soffit does not seem to significantly minimize the weight of the stairs as much as it provides a daring sense of suspension. The elliptical section could have been generated from joining the arcs of two circles, each based upon a stairwell dimension in plan, suggesting that the form in section, was ultimately derived using simple methods of geometrical proportioning.[14] It cannot be determined which ratio may have been the determining factor for the dimension of the stair structure, where the platform face thickness is 1/2 the landing width or where the stringer face depth is 1/2 the radius of the inside curve of the stair. Both together however, allow a smooth transition to occur between the face of the inclined vault and the cloistered vault of the stairwell. At the transition point between the rear spiral and inclined vaults an inflection appears. This is noticeable only from a specific angle Figure 8. This inflection has been graphically reproduced when the geometry of the stair is laid out on an incremental basis of plotting the rise over run for each step from landing to landing. Whether drawn by hand or by computer the inflection arises with this approach. It is suggested then that this was the method of layout for this stairwell and presents the limit of geometrical knowledge being brought to bear upon this general problem. This type of problem may have been observable with geometrical methods of Frezier, or Rondlet, and then possibly resolved.

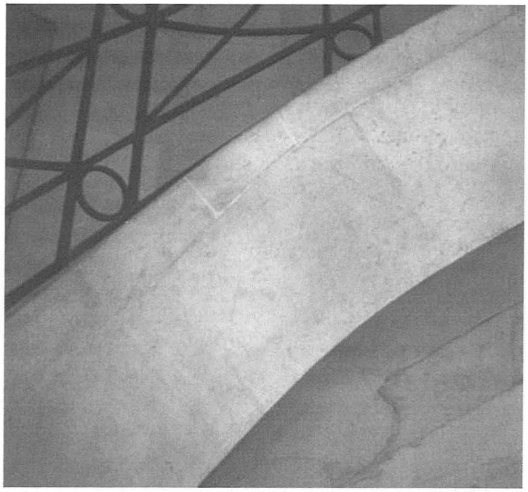


Figure 8

Cassini Salon vault analysis: (1672–1777)

The original design by Perrault for the main floor salon space is indicated in Figure 2. The plan essentially mirrored the first floor layout, having two intersecting cloistered vaults with a width of roughly 6.9 meters each. Replacing these vaults with a wider vault of 15.5 meters would accommodate the existing foundations, the spacing of the planned south elevation window piers, and the necessity to maintain the plan symmetry, which was an accepted strategy to assure structural stability. The intersection of the new vault with the south wall would have presented a serious problem to the elevation design if it remained a cloister vault. To retain the exterior elevation and the height of the building, a segmented barrel vault construction was required. This approach minimized the connection between the vault and the south wall. The remaining space in plan was covered by two narrower barrel vaults placed on each side of the southern portion of the main vault. This solution however, shifted the weight of the vault to the interior walls, increased the weight of the vaulting, reduced

the area of bearing by one third, and resulted in a loss to the constructive bond between wall and vault achieved in the rest of the design. Given these conditions, it is reasonable to think that the objective for the vault design was to keep its weight to a minimum by limiting its thickness so as to reduce the thrust on the abutments.

The first published drawings for the l'Observatorie appear in Claude Perrault's Vitruvius of 1673. The illustrations were prepared by LeClerc and present plan, section and elevations. While no construction is indicated in section, the suggested vault thickness is approximately 1.8m (5 ft. 11inches). Two undated drawings of the Cassini Salon vault, longitudinal section H79534, and transverse section H79536,[15] indicate stone construction details and fissures suggesting as-built accuracy. At the crown of the vault the construction is shown in both drawings as being comprised of a single voussoir in thickness covered by a thin plane of masonry to provide weather protection. The depth of the key stone, averaged from these two drawings and arrived at through interpolation by using field dimensions, is estimated as being 1.02 m (3 ft. 4 inches) in depth —a little more than half the depth suggest in Perrault's illustrations. Why a difference of this magnitude exists remains to be learned. The final dimension appears to have been close to the following, a one meter deep arch ring, with voussoirs of 4 degrees of thickness, for a desired clear span of fifteen meters. Using a late nineteenth century approach based upon empirical methods, an arch ring of 0.65m (2.12ft) would have been sufficient for cut stone construction.[16] Depending on the accuracy of these drawings, this would mean that the depth is more than sufficient.

In the Cassini Salon the radius of the vault near the crown was made as large as necessary to clear the flanking windows of the south elevation. The vault could not have had a much greater rise without also causing the re-design of the south elevation as well. At this point the vault thickness appears to have been a result of the availability of space as defined by the limits of the other elements of the design. The thickness and depth of the voussoirs shown are more or less consistent throughout the section, regardless of the dimension of the span, so no simple proportional relationship between span, radius, and thickness seems immediately apparent. A more practical approach is to examine the relationship between the

Figure 9

soffit (exposed face) of the keystone and its depth. This relationship of the height to width when examined across the voussoirs as shown in H79536 varies, but the extreme heights —both low and high, are shown as being 1.6 to 2.0 times the width of the face. Clearly the quality of construction played the crucial role in the stability of masonry vault construction. How the actual thickness was determined remains to be learned for this clearly was not an easy problem to resolve. As has been shown elsewhere, the concern to determine vault thrust was the focus of analytical attention from the 1690's through the end of the eighteenth century (Heyman 1996, 116–18).

Conclusions:

At the highly skilled end of the craft of building within the masonry tradition there is very little evidence that these masters had more to rely upon than a hard-won empirical knowledge and an informed intuition. And yet, in the presence of the work, there is a demonstrated sense of understanding, of a highly rationalized logic, that runs to the core of the material, to the form it was given, to the intersection and interdependence of elements, and the flow of space. It is difficult to argue in the presence of this form, or the shaping of the prisms, that analysis did not occur here.

The l'Observatoire de Paris exemplifies a coherence of design, of structural conception and a system of construction. Neither admiration nor fascination for this work has weakened its grip on this

author, or for any first class17th century French masonry construction. Antoine Picon clearly responds to the Observatoire, and the stairwell in particular, as a remarkable product of the collaboration between its architect Claude Perrault and the master masons (Picon 1988, 212–19). These sentiments are said to be broadly shared by those who are knowledgeable when shown this work.[17]

Is it possible that the principals inherent with the conceptualization and resolution of the l'Observatoire demonstrate an attitude that lies at the core of design in all admirable technological efforts? Perhaps the l'Observatoire could have been modestly refined, to be lighter, stronger, more amenable, or socially graceful. It is difficult to conceive however, that a significant improvement could be achieved without a significant change. In this sense, the design and fabric constitutes a seminal system that was the product of a special kind of thinking or attitude that is still prized today. What does this mean? The study of stereotomy may have done more than was originally expected in the XVIIIth century schools of engineering, beyond the development of a refined sense of spatial or even constructive logic, but to help convey an attitude as well.

The l'Observatoire de Paris was one of a handful of projects to achieve this degree of sophistication in the latter part of the XVIIth century. That this *class* of work might be thought of as seminal would mean that they contributed to the dispersion of an attitude as to how work should be conceptualized and conducted. This attitude goes beyond the general notion of excellence, and perhaps comes closer to a sense of teleological participation of all the elements that contribute to the making of a system. This can be observed in other scales of endeavor, whether for mechanical toys at French court, the precision clock, other buildings, or even in the massing of one's armies. In the wonderful work of Antoine Picon, there is a clear analysis of the transformation of how thinking changed from a classical to analytical rationality during the XVIIIth century in France (Picon 1992, Chapters 2 and 5). Because the l'Observatoire still commands admiration however, there appears to be a significant element of continuity from the classical or Vitruvian period of rationality that remains at the core of our own ideals in an era of analytical rationality.

Notes

1. This research was supported by the University of North Carolina Charlotte.
2. Ecole des Ponts et Chaussées 1747, based upon the introduction of scholastic training with the customary approach of apprenticeship based upon on the job training. (Sakarovitch 1995, 205–27). The Académie royale d'architecture (1671) began instruction to apprentice architects in «..applied mechanics, hydraulics, stone cutting, and civil and military engineering» within a few years of its founding. This institution is credited as «..the first higher technical school in France.» (Artz 1966, 29–34), (Picon, 1992, Ch.1).
3. I would like to thank Madame Danielle Michoud, le Service des Relations Exterieures of the Observatoire de Paris, and Madame Claudine Laurente, Astronomer, also of the Observatoire de Paris, as well as the Office of Herve Baptiste, Architecte en chef des Monuments historiques, Paris, for their generous gift of time and interest.
4. Cassini IV, 1810, Ch. 1. See also, Hahn 1971, Chapter I.
5. The lifetime's work of Tycho Brahe, a record of thousands of star positions in the night sky on the island of Hveen, was proving to be highly resistant to conversion to Parisian coordinates for confirmation of their accuracy or further practical utility. Johannes Kepler's conjecture that Mars moved in an elliptical orbit (1610) based upon Brahe's data, could not be verified conclusively and continued to be hotly debated. It was reluctantly decided among Academy members that recording astronomical data would have to begin from scratch (1673).
6. The south facade is a generous two stories in height and the general siting can be understood from the site and sectional drawings. The unadorned north facade presents a stern attitude due in part, to the vertical scale of the massing. The south face however, appears very well proportioned and approachable.
7. A corresponding detail from the frontispiece of Perrault's Histoire des Animaux prepared by Sebastien Leclerc, also suggests the construction proceeded layer by layer, evenly throughout construction. (Sebastien Leclerc, «Louis XIV being shown round the Academy of Science by Colbert», 1671).
8. The methods of construction used here could have suited a generally unskilled work force with a minimum number of skilled masons (3 or 4), on site at most times. The methods would have permitted one master mason to have been in control of the work without being overwhelmed and yet maintain high standards of precision through the use of templates or jigs, simplifying the ordering of materials from the quarry, and insuring a consistency of effect from the exterior to

the interior. These methods would have allowed the workers to address tasks systematically, being confronted by only one or two tasks of construction at a time. The tasks could be as repetitious as the stone from the quarry would permit. The implication is that the master mason and his principal assistants had to have a good understanding of the total project for this to occur, which means that careful drawings for the general construction would have had to have been prepared.

9. His mathematical work initiated a century of development on conic sections among French savants. His method of projective geometry was rejected by the professors at the Academie Royale and masons alike, for different reasons, despite the concerted efforts of Abraham Bose. (Schneider 1983).
10. Desargues countered that he was not a craftsman and that his intention was to improve the methods of geometric projection and not necessarily improve the craft of construction. (Schneider. 1983. Ch. II).
11. The traditional methods for cutting stonework with warped surfaces and compound curvatures appear embarrassingly simple when described in 19th century texts. A method of «parallel rules,» for cutting plane surfaces: Two drafts or channels are cut as close as possible to the same plane into the rough surface of a stone. Into each grove is placed a wooden rule of constant dimension so that its lower and upper edges are parallel to one another. A level is placed across both rules and sighted across the length of each to insure that the drafts are perfectly level with one another. Two additional drafts are cut to the same plane and then if no additional drafts are needed, the remaining stone between the drafts can be removed to produce a plane surface. To cut a warped surface, a method of «twisting rules» was employed. In this approach one rule has a constant dimension along its length while the other starts out at the same dimension at one end but then increases along its length. Again, drafts are cut into a coarse stone face and the rules inserted. This time one draft will have an increase of depth along its length so that the exposed edge of each rule will be in plane with one another and confirmed by testing with a level. To insure that the warping of a surface is constant from stone to stone through a course or across several courses, the drafts must be sunk and rules maintained at a constant distance apart from one another as applied from stone to stone. This distance was maintained by simply boring two holes through each rule and stringing a knotted a piece of twine through each to maintain a constant distance between each rule where ever they were applied. A stone with compound curvatures would have several rules applied to it during cutting. The trick is determining the angle at which the twisting rule to be cut at and the distance at which the rules are to be kept apart. However, this problem is not overly difficult when the problem is being solved at full scale either graphically or on site. These techniques were probably employed across each surface of the stones, the facings, sides and backing as needed. (French, 1902, 26–34).
12. This approach of producing an inclined helical prism with vertical joints requiring cramps for support can be found in Frezier (1980) Figure 193, Plate 106, page 306–7.
13. Dimensions of the vaults in the stairwell were determined with the use of a pulse laser ranger finder, on site, during June of 1999. The vault dimensions show the curvature to be an ellipse whose arc falls outside the dimensional of the stairwell. The ellipse may have been generated by using two circles placed with their arcs tangent to the spring line of the vault, one whose diameter is 1/2 the width of the stair and the other whose diameter is the full width of the stair, which fall upon most of the points of the arc of the vault. The form was more likely the result of structural necessity than formal desire, as the suspended edge of the stairwell would have been kept as narrow and therefore as light a weight as possible. These lines could have been drawn within the limits of the stairwell construction, probably on the landings. This form has the pleasant effect of capturing and reflecting daylight better than a singular circular arc form would have permitted.
14. A recent investigation by Robin Evans of Philbert Delorme's 1550 method of preparing traits suggests that a graphic method may have existed that would have had sufficient accuracy to permit an approximate dimension of prisms to have been found, but was incapable of preparing descriptive forms. For a description of Philbert Delorme's method of producing traits, see, Evans 1995, ch 5). On the advise of Mr. A. W. French, a late 19th century expert in stereotomy: if the form is too difficult to be defined by calculation then the approximate solution must be arrived at by drawing alone —and the accuracy of drawing alone was not sufficient for good masonry construction. No finish dimensions should be taken from the projections since the reduced scale of the drawings would not allow a sufficient accuracy nor account for the changes that creep into a project due to the necessities of construction. The final responsibility for accuracy of construction must be the stonemason's, who is expected to make full scale working drawings and then find the finish dimension of each prism in situ. (French 1911, Ch. 2).
15. Archival drawings listed in Bibliotheque Nationale, film Va 3041/1, longitudinal section H79534, and transverse section H79536. H79536 may be viewed in Picon, 1988, ill. 179, page 215.
16. Trautwine's formula is used here since it is empirically

based. With an interpolated dimension of the upper vault radius of 10.38m (34.05'), and 7.75 m (25.42') for one half the vault span suggests that the keystone depth for cut stone construction should be about 0.65m and for first class late 19th construction, the depth could be as little as 0.61m (2.0'). Snelling, 1952, 319–329.

17. In conversation with Madame Claudine Laurente, Astronomer, and Observatoire Historian who has provided tours to numerous architectural groups though the building.

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The drawings on stone in Galicia: Types, uses and meanings

Miguel Taín Guzmán

Drawing has been and it still is the principal means of expression for the architect, in addition to being the base of all the arts.[1] Indeed, in the genesis of every retable and building there is a master model, signed by the mentioned creator, as well as drawings and patterns belonging to the artist's workshop, which were partially executed at times to be used in the construction site by the architect's assistant and his workers. As paper is fragile, expensive and not very practical, in Galicia during the 16th, 17th and 18th centuries the usual choice is drawings on stone [in Spanish «*monteas*»], that is, architectonic outlines made directly on the stone or engraved in it; frequently on the floors and walls of the actual construction site.

The first European examples belong to Hellenic Greece,[2] where as the oldest in Spain were found in Itálica.[3] During the period of this present study, their knowledge was compulsory to pass the exams to become an architect's assitant or a master architect.[4] The most common ones represent supports, arches and vaults, especially when they were larger in dimensions. Not only the components of the columns and pilasters but also the voussoirs of an arch or a vault have different shapes and their sizes and proportions had to be rigorously taken into account. Otherwise, it would provoke irregularities and deformations that would affect the look, symmetry and beauty of the work, as well as its safety and solidity.[5]

We have examples of their usage in Galicia in documents dating from 1669 to 1671, referring to the construction of some parts of the Baroque furnishings of the main chapel of the cathedral of Santiago de Compostela, according to plans hewn into the floor of the cloister,[6] and also a document from 1675 regarding the casting of the bell called «*de la Concepción*», from the bell tower of the same cathedral «*en conformidad del modelo y tamano de vn debujo que se ha de haçer en las claustras de dicha Santa Yglesia*».[7]

Nevertheless, the best examples are the testimonies I have found in the last four years in cathedrals, monasteries and churches of the four provinces of Galicia.[8] There are not many left because the usual procedure was to erase them after their use, polishing the stone or covering them with various materials. The ones found expand the repertoire of this type of drawing, adding to others in Spain and Europe, such as the ones in the cathedral of Seville,[9] the Rosslyn Chapel or the cathedral's of York and Auxerre.[10] All of them exemplify the practice of this common technique of planning, in which the Galician master builders reached a great level of expertise.[11] This is shown in the drawings on stone of the column, the bracket, the pediment and the straight arch located in the cathedral of Santiago; the abbatial stairs of the monastery of Montederramo; the entablature of the façade of San Telmo in Tui and the interior of the church of the monastery of Poio; the rib-vaulting of the cathedral of Tui and the church of Montederramo; the cross-vaulting of the college of Monforte; the arch of the monastery of Poio, among others.

In the investigation of them, it is very interesting to compare these drawings with the ones included in Spanish manuscripts of stereotomy from the 16th, 17th and the beginning of the 18th century, mainly devoted to the application of geometry to the design of arches and vaults.[12] They are the *Cerramientos y Trazas de Montea* by Ginés Martínez (1556–1620),[13] the *Libro de Traças de Cortes de Piedra* by Alonso de Vandelvira (1575–1591)[14] and the *Cuaderno de Arquitectura* by Portor y Castro (1708–1719),[15] and the first and the third examples have some connections to Galicia.[16] It is clear that the Galician master builders used this type of manuscript, which have since been lost. The only testimonies of their skill in the art of stone cutting that remain are the finished buildings and the patterns we want to analyse.

We do have documentation of the usage in the few books on the topic published in the 17th and 18th centuries.[17] Domingo de Andrade, Master Builder of the cathedral of Santiago, was familiar with *Arte y Uso de la Arquitectura* (Madrid, vol.I, 1633 and vol.II, 1665) by Fray Lorenzo de San Nicolás, which includes several chapters devoted to the art of stone cutting.[18] The same title was in the libraries of the architects and master builders Diego de Romay,[19] José de Seixas,[20] Fernando de Casas,[21] Lucas Ferro Caaveiro and Fray Manuel de los Mártires. The books of these last two men are now kept in the Biblioteca Xeral (Central Library) of the University, with their ex libris intact.[22] There are also other volumes about perspective, arithmetics and geometry, in some ways related to the topic, among the belongings of artists such as Juan Bautista Celma,[23] Simón de Monasterio,[24] Francisco de Antas,[25] Diego de Romay,[26] Domingo de Andrade,[27] Fray Gabriel de Casas[28] and Fernando de Casas.[29]

Significantly, in the library of the cathedral of Santiago there is a *Tratado elemental de los cortes de cantería, o arte de la montea* by Simonin, translated into Spanish by Fausto Martínez de la Torre and José Asensio (Madrid, 1795),[31] and the two volumes of the *Arte y Uso* by Fray Lorenzo (the edition published in Madrid in 1796),[31] already mentioned and used by the artists of the cathedral's workshop. In the library of San Martín Pinario there is another copy of *El arte de la montea* by Simonin.[32] And the old volumes of the Biblioteca Xeral, which came from the expropiation of the libraries of monasteries and convents of the city when the Disentail [«*Desamortización*»], from the libraries of the Jesuit Colleges of Santiago and Monterrei occurred after the expulsion of the Jesuits and from the purchasing of private libraries (as we can see from the ex libris of the books), include the two cited editions of the two volumes of Fray Lorenzo, property of Lucas Ferro Caaveiro (Madrid, vol.I, 1667 and vol.II, 1665)[33] and Fray Manuel de los Mártires (Madrid, 1736);[34] the *Breve tratado de todo género de bóvedas* by Juan de Torija (Madrid, 1661),[35] that came from the library of the convent of Santo Domingo de Bonaval[36] and contain the explanation of the different ways to build a vault; five copies of the volume V of *Compendio Matemático* by Tomás Vicente Tosca (two from the Madrid edition of 1727[37] and three from the Valencia edition of 1757)[38] and their treatise, entitled *De la montea y cortes de la cantería*; two editions of *El Arquitecto Práctico* by Antonio Plo y Camin (Madrid, 1767[39] and 1793[40]), which contains chapters on how to build arches, squinches, domes and vaults; and two copies of the volume IX, Part I of the *Elementos de matemática* by Benito Bails (Madrid, 1796),[41] also containing fragments on the same topic. There is also a 19th century edition of the *Geometría Descriptiva* by Gaspar Monge (Madrid, 1803).[42]

Having considered all this information, we can study the practical application of the theoretical knowledge from the cited bibliography. We will classify the drawings on stone found according to their function and their particularities. I must point to the difficulties of interpreting the gathered material, especially some of the incomplete or heavily damaged drawings or the ones located in buildings that lack a detailed historic monography.

Drawings on stone of bases

On the west wall of the cloister of the cathedral of Lugo there is an ortogonal network of red lines that is preserved and that covers the whole wall. On it you can see the profiles of the base of a column or pilaster[43] (fig. 1). They consist of the canonic plinth, torus, scotia, fillet and the beginning of the fust. They belong to the Tuscan order, published in the *Regla de los Cinco Órdenes de Arquitectura* by Vignola. The wall where they are engraved is older than the present cloister, which replaces a previous wooden one, and

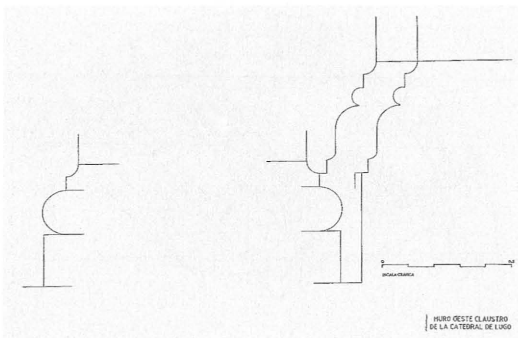


Figure 1
Drawing on stone of support base; cathedral of Lugo (drawing by José Manuel Yáñez Rodríguez)

this wall is part of the *Palacio Capitular* built by Domingo de Andrade in 1683.[44] So it would be a logical link between the drawing and the cloister, which contains huge Tuscan pilasters and built by Fray Gabriel de Casas and Fernando de Casas between 1708 and 1714.[45] And, in fact, the elements drawn in the profiles are repeated in the building but with very different measurements, so they could be not related.

But, on the floor of the gallery of the third floor of the *Palacio Capitular* of the cathedral of Santiago (nowadays the Cathedral's Museum) there is another drawing which does correspond with the columns of the gallery (fig. 2). As Rosende Valdés has proved, that gallery is the result of a 1588 renovation of the *Palacio Capitular* built several decades before according to Rodrigo Gil de Hontañón.[46] It has thirty-three Ionic columns and several pillars, joined by a parapet and with the particularity of having a «*zapata*» between the capital and the entablature. The drawing on stone includes the pattern of the plinth of the base and the apophyge of the fust of the column.

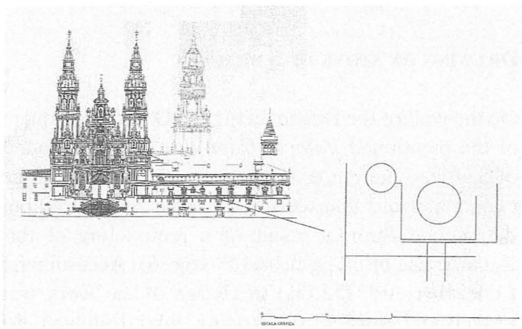


Figure 2
Drawing on stone of column base; cathedral of Santiago (drawing by José Manuel Yáñez Rodríguez)

Drawing on stone of a column

On the floor of the first story of the cited Compostelan building there is a drawing of what looks like a classical column with its base, fust and astragal of the capital (fig. 3). The base consists of pedestal, plinth, torus and fillet and, in a geometrical feat, is projected with the same measurements in an angle of 90º. The fust does not have entasis and above it there is an outline of the capital and maybe part of the entablature. Its function has not been identified and, according to its characteristics, I doubt that there is a simple exercise of planning with didactic purposes and whitout an immediate practical use in the building of the cathedral. As in other cases, the drawing on stone corresponds with the illustrations of the Tuscan order published in the editions of Vignola.

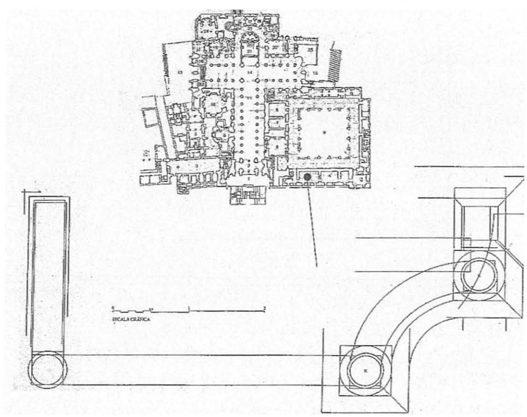


Figure 3
Drawing on stone of column (?); cathedral of Santiago (drawing by José Manuel Yáñez Rodríguez)

Drawings on stone of capitals and entablatures

There are two discoveries and both are examples of Baroque architecture. The oldest one is an elaborated pattern of the piers of the crossing of the church in the Benedictine monastery of San Xoán Bautista of Poio (Pontevedra), a building from the end of the 17th century and the beginning of the 18th (fig. 4).[47] It consists of the profile of the Tuscan capital, formed by the canonic fust, fillet, astragal, gorgerin, listels, equinus, abacus and listels clearly differenciated, combined with the profile of an entablature of the Ionic order, composed of an architrave divided in fascias, moulding, frieze, moulding, dentil, three quarters of a bead moulding, throating, corona and eaves. Once again, the referent is the book by Vignola.

The drawing on stone is located on the east wall, on the bottom aisle of the processional cloister. As it belongs to the previous century and there is a big door that connects it with the new temple, it is logical that the master stonecutters worked there, finding shelter from the weather under its vaults. In fact, on the floor near that drawing there are more, supposedly also related to the construction of the new church, but today it is impossible to read them because the stones have been moved from their original location.

The other drawing on stone is located in the narrow space of the top choir-loft of the church of San Telmo in Tui, built from 1769 on by the Portuguese architect

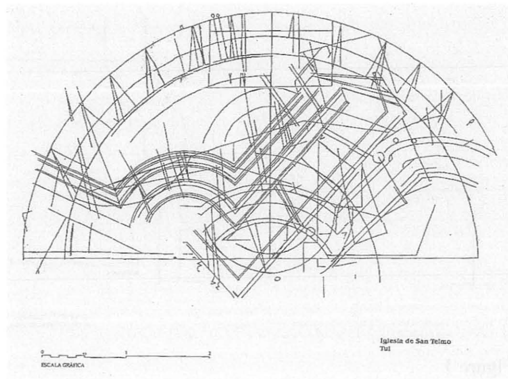


Figure 5
Drawing on stone of entablature of the façade of the church of San Telmo in Tui (drawing by José Manuel Yáñez Rodríguez)

Fray Mateo de Jesús María, following his own building plan. That, as Rosende Valdés has studied, shows the influence of the Baroque style from Braga.[48] The drawing is the most elaborate of Galicia and relates to the edge of the main façade of the building (fig. 5). The façade has three parts and in both lateral ones you can see the first floor of two towers that were never finished.[49] Such structures have two Corinthian pillasters set at an angle and share a dynamic and broken entablature, that corresponds with most of the found drawing on stone.[50] In it we notice the curve formed by the three fascias of the architrave, the frieze and the dentil, and also the acute angle of the eaves and the cymatium.

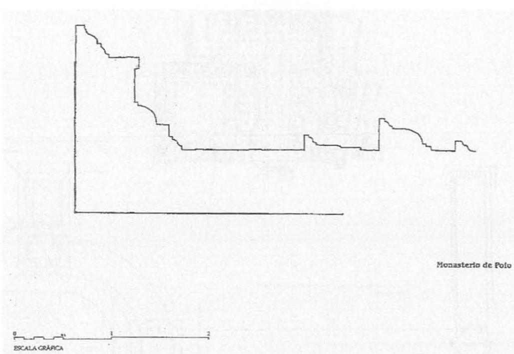


Figure 4
Drawing on stone of entablature of the crossing of the church in the monastery of Poio (drawing by José Manuel Yáñez Rodríguez)

Drawing on stone of a bracket

On the wall of the façade facing the Obradoiro Square of the mentioned *Palacio Capitular* of the cathedral of Santiago there is a drawing on stone of one of the twenty brackets that support the projecting balcony of the second floor, a result of a remodeling of this Renaissance building in 1614[51] (fig. 6). According to López Ferreiro, the one in charge of the work was Francisco González de Araújo, who followed the building plan of Jácome Fernández, Master Builder of the cathedral.[52] The drawing consists of a curved profile of the overhanging element that supports the

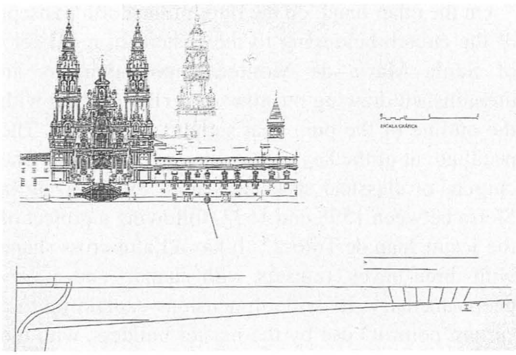


Figure 6
Drawing on stone of brakets of the balcony of the Palacio Capitular of the cathedral of Santiago and drawing on stone of straight arch (drawing by José Manuel Yáñez Rodríguez)

weight of the afore mentioned structure. It is related to the straight arch that we will explain next.

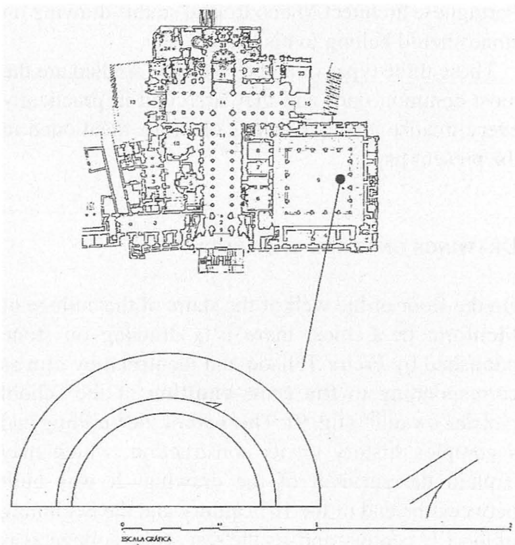


Figure 7
Drawing on stone of semicircular arch; cathedral of Santiago (drawing by José Manuel Yáñez Rodríguez)

Drawings on stone of arches

The most frequent drawings on stone are the ones related to arches, with their different types and functions. For example, in front of the mentioned *Palacio Capitular* of Compostela, on the bottom floor, on the left of the present entrance, there is a drawing on stone of **a straight arch,** with the desing of its voussoirs in a wedgelike fashion, perfectly drawn (fig. 6). As we have already noted, by it there is a drawing on stone of the brackets that support the balcony of the second floor, built in 1614, so we can relate both drawings with that construction, and date them around that year.[53] Nevertheless, the number and the position of the voussoirs in the lintel does not fit with any of the openings that now exist in that wall, not even with the immediate gateways that could be connected to it. The projet was not complicated for the author because the same one is included in Ginés Martínez[54] and any of the later manuscripts and books about the art of stone cutting.

Beside this, on the slabs on the floor of the cloister of the same cathedral, there is another drawing on stone representing a **semicircular arch** (fig. 7), whose chronology and function are unknown.

On the floor of the top aisle of the processional cloister of the monastery of Poio **a basket-handle arch** is engraved and, as in the first arch, there is a drawing of its voussoirs (fig. 8). It corresponds to a nearby access, in the north aisle. Bonet Correa dates the construction of the cloister in the second half of the 16th century and ascribes its completion to the

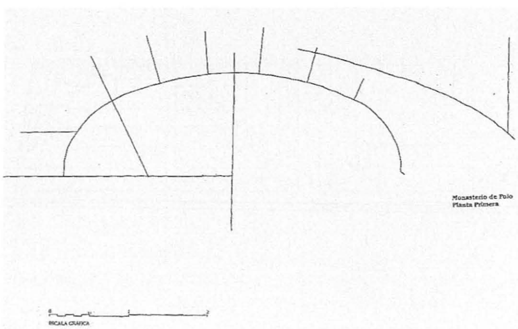


Figure 8
Drawing on stone of basket-handle arch; monastery of Poio (drawing by José Manuel Yáñez Rodríguez)

Portuguese architect Mateo López, so this drawing on stone should belong to his work.[55]

These three types of arches we have studied are the most common ones and they are cited in practically every treatise about drawings on stone mentioned in the present paper.

DRAWINGS ON STONE OF VAULTS

On the floor of the well of the stairs of the college of Monforte de Lemos, there is a drawing on stone published by Freire Tellado and identified by him as corresponding to **the cross-vaulting** of the school cloister's vault[56] (fig. 9). This part of the building had a complex history on its construction, which may explain the survival of the drawing. It was built between the end of the 16th century and the beginning of the 17th century and, as the rest of the college, was sponsored by the cardinal Rodrigo de Castro, following the project of the Jesuit Andrés Ruiz and Vermudo Resta, the latter from Milan.[57] The documentation informs us of the use of drawing on stones —*«monteados»*— from the onset of the construction.[58]. The drawing found consists of a cross-vaulting of uneven sides and with semicircular arches in its elevations. The measurements and shapes of the carving of the voussoirs of the structure are specified, in addition to its decorative fascias.[59]

On the other hand, on the floor of the north transept of the church belonging to the Cistercian monastery of Santa María de Montederramo, there is an unpublished drawing on stone of **a rib-vaulting** with the outline of the piers that support it (fig. 10). The peculiar cut of the keystone ashlar is remarkable. The church, of classical style, was built by Pedro de la Sierra between 1598 and 1632, following a project of the Jesuit Juan de Tolosa.[60] It has a Latin-cross shape with three naves, transept with chapels and a very deep sanctuary. Its wide dimensions explain up to a certain point its use by the master builders, who did not have a more appropiate shelter and drew on the floor sketches for this and other remodelling efforts, as we will examine below. Later in the 18th century the top choir-loft was built or expanded above the nine rib-vaultings, covering the three first sections of the naves. The drawing on stone corresponds to that work and in fact its measurements coincide with the ones of the central vault of the third section, whose keystone bears the inscription «IHS. MA. 1772», referring to the date of the conclusion of the work.

Iglesias Almeida published the news about a drawing on stone on the floor of the Santa Catalina,[61] chapel of the cathedral of Tui, which corresponds to **a star vault** with its keystones, ribs and liernes[62] (fig. 11). This chapel belongs to the *Palacio Episcopal* built by the bishop Diego de Muros at the end of the 15th century.[63] Apparently, at the beginning the

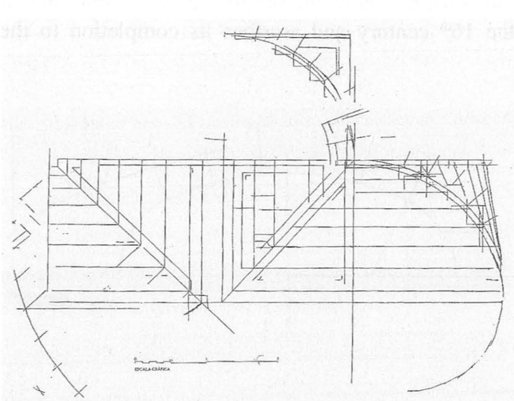


Figure 9
Drawing on stone of cross-vaulting of the cloister of the schools of the college of Monforte (drawing by José Manuel Yáñez Rodríguez)

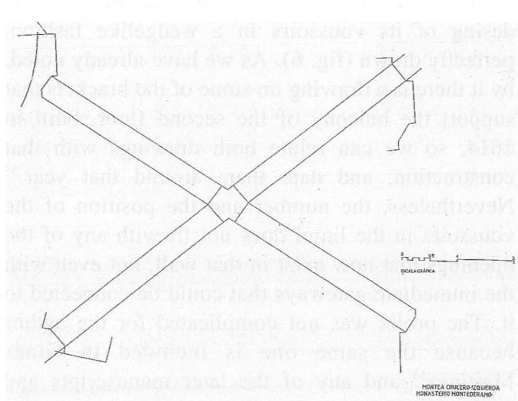


Figure 10
Drawing on stone of rib-vaulting of the top choir-loft of the church of the monastery of Montederramo (drawing by José Manuel Yáñez Rodríguez)

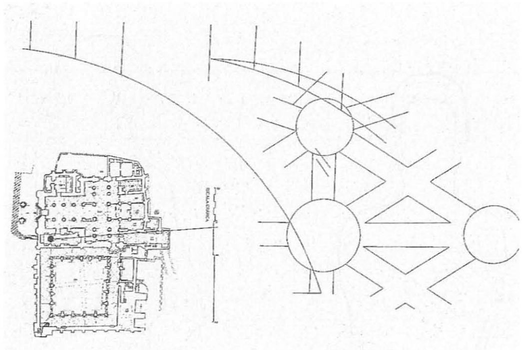


Figure 11
Drawing on stone of star vault; cathedral of Tui (drawing by José Manuel Yáñez Rodríguez)

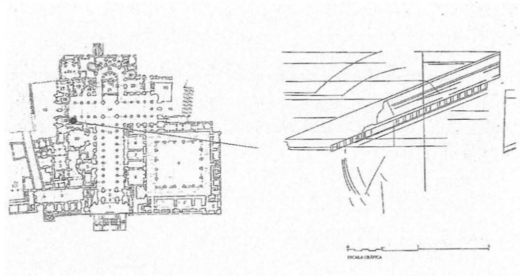


Figure 12
Drawing on stone of pediment from the façade of Azabachería of the cathedral of Santiago (drawing by José Manuel Yáñez Rodríguez)

building had only three sections, which today are the nave, and the drawing was located on the first two sections. The fourth section of the sanctuary was added in 1726.[64] The present vaults of the building are cross-vaultings but they date from the 18th century and replaced older ones of an unknown shape.[65] Probably the drawing on stone is related to some of the vaulting built during the 16th century in the cathedral, although what we have today (crossing-vault, main chapel, sacristy and old San Telmo chapel) do not correspond exactly with the drawing.

The first type of vault cited, very frequent in the Galician architecture of the time, is included in the manuscripts of Vandelvira[66] and Juan de Portor and in the treatises of Juan de Torija and Fray Lorenzo de San Nicolás, among others, which means that the author could count on multiple sources for its elaboration. In the cases of the rib vault and the star vault, the sources are more complex due to their Gothic origin. In any case, it would be useful to contrast the ones in this paper with those included in the manuscripts by Simon García, Hernán Ruiz *«el Joven»,* Vandelvira and Juan de Portor.[67]

Drawing on stone of a pediment

On the floor of the north transept of the cathedral of Santiago, engraved on the floor itself, there can be found the only known drawing of a pediment (fig. 12). It is well known that the construction of the Azabachería façade began in 1758, following a Baroque plan by Lucas Ferro Caaveiro, the Cathedral's Master Builder. Nevertheless, this artist was removed from the project, probably due to the growing relevance of the Academy of San Fernando all over Spain, and his plan was corrected by the architects from the Academy Ventura Rodríguez and Domingo Lois Monteagudo. They both abandoned the original building plan, using in its place one more connected to the classical Baroque Italian architecture; and their talent is patently obvious in the second floor and the ending.[68]

The located drawing belongs to this second renovation and corresponds to the two Ionic pediments that crown the lateral sides. In it we can see the drawing of a classical triangular pediment with the characteristic denticular cornice. The influence of the engravings from the architecture treatises of the time, the sources of that item, is evident (for example Vitruvio, Arfe, Serlio, Labacco, Caramuel and so on).

Drawing on stone of stairs

I have only found one example. It is the drawing of the abbatial stairs of Montederramo, located on the stone paving slabs of the south transept of the church (fig. 13). It was built in the period that this article addresses to connect the two floors of the cloister and it has suffered a recent and very aggressive remodeling. It is composed of three flights enclosed

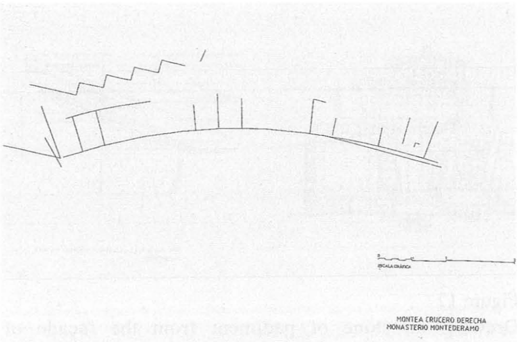


Figure 13
Drawing on stone of abbatial stairs of the monastery of Montederramo (drawing by José Manuel Yáñez Rodríguez)

by a set of balusters recently arranged in an oblique perspective.[69] The drawing shows the steps and the segmental arch of the last flight, with the exact number of voussoirs.

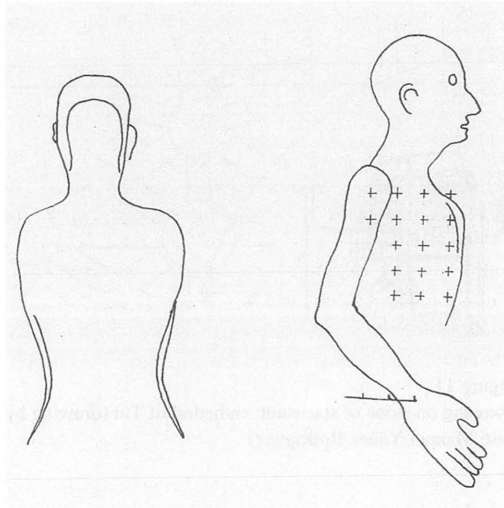


Figure 14
Drawing on stone of Virtues from the tabernacle of the cathedral of Santiago (?) (drawing by José Manuel Yáñez Rodríguez)

A special case: The two humanoid drawings on stone of the Cathedral of Santiago

Two figurative drawings on stone found on the floor of the Goya Tapestries Hall of the Compostela Cathedral's Museum deserve special attention (fig. 14). They are two anatomical studies of a bust seen from the front (or back, it is not clear), with a height of 2.3 metres, an a profile (measuring 2.8 m). The second has the particularity of still having the ortogonal grid and the scale. Both are reminiscent of similar studies by Durero[70] and Juan de Arfe, the latter one published in his *Varia commesuración para la escultura y arquitectura* (first edition of 1585),[71] and included in the personal libraries of the Galician artists, as I mentioned above.

The function of both drawings should be related to the approximate rendering of the human body's dimensions and its proportions, to be later applied in works of sculpture.[72] In this scene, the only place in the cathedral where numerous images where carved was the Baroque furnishings of the main chapel, made up by the wall revetment, the *camarín* and the tabernacle, built between 1658 and 1677.[73] In fact, the revetment has forty-four angels holding lamps; the *«camarín»* has a Saint James Pilgrim and four kneeling kings; and the tabernacle has eight flying angels which hold the structure, the four Cardinal Virtues, a Saint James *«Matamoros»,* four Turks and ten porter angels that used to hold banners.

This use of drawings on stone for the scultoric plans is not so rare if we consider its use for the construction of the architectonic structure: its use is mentioned in the 1669 agreement about the revetment of the two penultimate piers of the sanctuary, which used to hold a bar of iron with votive lamps. They should be made *«conforme* [a] *la planta que está disinada en el losado del claustro y* [luego] *puesta en vn tablero».*[74] Also, the 1670 contract says that the cornice of this covering should be made *«conforme* [a] *la planta que iço Domingo de Andrade, aparejador de la obra del tabernáculo, en el losado y claustra de dicha Santa Yglesia».*[75] And the 1671 contract of the revetment of the first two piers had to follow the plan *«puesta en el losado del claustro».*[76] The relative proximity to the hall with the Goya Tapestries, with the thrice times mentioned cathedral cloister, the place where the different pieces of the

furnishings where carved and held until their assembly in their precise locations is also significant.[77]

It is also similarly useful to compare both drawings with the busts (profile and volume) of the Fortitude, Prudence, Justice and Temperance of the tabernacle, that were made by the sculptor Pedro del Valle from Villafranca del Bierzo and were commissioned in 1667 along with the images of the eight angels that support the tabernacle and with the Pilgrim Saint James and the four kings that pay homage to him in the *«camarín»*.[78] The chronological closeness to the already mentioned and documented architectonic drawings on stone should not be considered a mere coincidence. In fact, in the document of the agreement it is specified that the angels should be carved following the model and the *«tamaño de otro que está echo»* of one made by sculptor Blas do Pereiro and that Saint James and the kings should be made following the patterns of Pedro de la Torre, a carver from Madrid. On the other hand, the virtues should be *«del tamaño de las figuras de la traça, según el pitipie»*, probably meaning our drawings on stone.[79]

From the global study of all the drawing on stone so far located in Galicia we can reach interesting conclusions. Most of the examples are in the cloisters of the cathedral of Santiago, the cathedral of Lugo and the monastery of Poio, due to the fact that they have ample and ventilated covered halls, where the master builders would have worked all year long without being bothered by the hassle, noise and dust generated by their work.[80] On the other hand, in some other monasteries they are on the floor of their ample churches (in Montederramo, for instance), maybe because they are places easily isolated with movable walls from the rest of the building. It is not by chance that the drawings are related to the construction of the top choir-loft. And lastly, in some other temples they use other marginal spaces, mainly the galleries (like in the cathedral of Santiago and the church of San Telmo in Tui). All of these locations are the reason that most of them are lost because many buildings have been renovated in terms of their floorings, specially in the last decades.

A special chapter should be devoted to the drawings carved into stone on the floor of the first story of the *Palacio Capitular* of the cathedral of Santiago. We are only analysing a classical column[81] and its location in that place could be related to the establishment of the cathedral's workshop of artists, which then occupied that same area during a long period of time. That is the only explanation of the number and superposition of drawings.

All the drawings on stone examined are carved directly into the granite of floors and walls, in contrast with the techniques used elsewhere, like the drawings on ceramic surfaces of the cathedral of Seville,[82] or over lime mortar in the so-called «Hall of Drawings» of the same building.[83] In its making they used tools of the stonecutters, like chisels, rules, squares, ropes, big dimension compasses, tracers and patterns. There are good examples in the ethnographic collections about the trade in the Museo do Pobo Galego or the Olimpio Liste Collection. In several inventories of the possessions of architects and master builders we found these types of instruments, although it is not clear whether they were used for drawing on paper or stone.[84]

There is an evident relationship between the different drawings on stone and the *Regla de los Cinco Órdenes de Arquitectura* by Vignola (as in the base of the cathedral of Lugo, the column in the cathedral of Santiago and the entablature of Poio), which is not strange because that book is the principal manual of the architects and master builders of that time. This author's work is present in their libraries (he is included in the ones of Simon de Monasterio,[85] Diego de Romay[86] and Fernando de Casas[87]) and also in the contracts as the model to follow in a construction project. Some examples are the adjustment of the church of the college of the Jesuits of Monforte[88] or the cloister of the abbots in the monastery of Santo Estevo de Ribas de Sil.[89] Moreover, in the holdings of the Biblioteca Xeral there are three editions of the book, two Italian ones (Roma, 1602[90] and 1732[91]) and one Spanish (Madrid, 1792)[92] and in the library of San Martín Pinario there is one, published in Madrid in 1760.[93] On the other hand, we should take into account that other later experts in architecture had published the five orders of Vignola (such is the case of Fray Lorenzo de San Nicolás, Tosca, etc.) and those books could also be used when drawing.

The repertoire of drawings on stone presented here prove the possibilities of the Galician architectonic design and shows that although we know that most Galician master builders were illiterate (many could not even write their signature), they would have had basic notions of and practical experience with geometry, and they used that knowledge in their

professional endeavors.[94] In any case, although we do not have drawings on stone of all of our buildings, the detailed study of Galician cathedrals, monasteries and pazos during the Modern Period should lead us to a reflection on the topic.

NOTES

All the reproductions of drawings on stone that illustrate this article were made by José Manuel Yáñez Rodríguez, Technical Architect of the Diputación Provincial of Coruña, and Professor of the University of A Coruña. I also owe him a good number of ideas and suggestions reflected in this article. Augusto Fernández González, José Manuel Rodríguez Pérez, Francisco Xavier Novo Sánchez, Miguel A. Cajigal Vera and Adriana Candela Cousillas Lino helped him with the drawings. Pablo Yáñez Rodríguez did the computer work. I wish to express my gratefulness to all of them.

1. See Checa, F., «El dibujo, fundamento de las artes», A Distancia, Teorías e historias de los dibujos de arquitectura, octubre 1991, 8–10.
2. See Ruiz de la Rosa, J. A., *Traza y Simetría de la Arquitectura,* Sevilla, 1987, 124–128.
3. See Pinto, F., and Jiménez, A., «Monteas en la Catedral de Sevilla», *Revista de Expresión Gráfica Arquitectónica,* 1993, nº 1, 79.
4. See Marías Franco, F., «Trazas, trazas, trazas: tipos y funciones del dibujo arquitectónico», *Juan de Herrera y su influencia,* Actas del Simposio Camargo, 14–17 julio 1992, Santander, 1993, 351–353.
5. Even today the practice of drawings on stone is recommended for specific cases (see *Guía práctica de la cantería,* Escuela Taller de Restauración Centro Histórico de León, León, 1993, 197).
6. We will talk about it below.
7. A.C.S., Varia, leg. 718, doc. 484.
8. Some of them, located in the cathedral of Santiago, were published by me some years ago in my books *Trazas, Planos y Proyectos del Archivo la Catedral de Santiago* (A Coruña, 1999); and «Los aparejadores gallegos en la época moderna (siglos XVI-XVIII)», *El Aparejador y su Profesión en Galicia,* Santiago, 2001, 113–115.
9. See Pinto, F., and Jiménez, A., art. cit., 79–84; Ruiz de la Rosa, J. A., and Rodríguez Estévez, J. C., «Monteas en las azoteas de la Catedral de Sevilla. Análisis de testimonios gráficos de su construcción», *Actas del Tercer Congreso Nacional de Historia de la Construcción,* Sevilla, 26–28 octubre 2000, vol. II, 965–978.
10. See Ruiz de la Rosa, J. A., *Traza y Simetría . . . ,* op. cit., 280–290. About French technical treatises see Savignat, J. M., *Dessin et architecture du Moyen-Âge au XVIII siècle,* Paris, 1980, 135–143.
11. For a general overview of the Galician master builders and stonecutters see Fernández Álvarez, Mª. A., *Arte y sociedad en Compostela 1660–1710,* Sada-A Coruña, 1996; Taín Guzmán, M., *Los arquitectos y la contratación de obra arquitectónica en la Galicia Barroca (1650–1700),* Sada-A Coruña, 1997; Goy Diz, A., *Artistas, talleres e gremios en Galicia (1600–1650),* Santiago, 1998.
12. See Bonet Correa, A., «Los tratados de montea y cortes de piedra españoles en los siglos XVI, XVII y XVIII», *Figuras, modelos e imágenes en los tratadistas españoles,* Madrid, 1993, 105–118; Rabasa Díaz, E., *Forma y construcción en piedra. De la cantería medieval a la estereotomía del siglo XIX,* Madrid, 2000, 204 on. For the identification of drawings on stone is also useful Palacios, J. C., *Trazas y cortes de cantería en el Renacimiento Español,* Madrid, 1990.
13. Facsimile edition published by the Servicio Histórico Militar (Madrid, 1986) with an introductory study by Bonet Correa, A., «Ginés Martínez de Aranda, arquitecto y tratadista de cerramientos y arte de montea», 13–34. The same work was also published as a chapter of his compilation book cited above *Figuras . . . ,* op. cit.
14. Facsimile edition published by the Caja de Ahorros Provincial de Albacete (Albacete, 1977) with an introductory study by Geneviève Barbé-Coquelin de Lisle.
15. Not published in facsimile. There are only some extracts of the text in Taín Guzmán, M., «O Barroco», *Fontes Escritas para a Historia da Arquitectura e do Urbanismo en Galicia (Séculos XI-XX),* vol. II, Santiago, 2000, 765–775.
16. About the first one see BONET CORREA, A., «Dos ejemplos de corte de cantería de Ginés de Aranda en Santiago de Compostela», Figuras . . ., op. cit., 141–145. For the second see TAÍN GUZMÁN, M., *Domingo de Andrade, Maestro de Obras de la Catedral de Santiago (1639–1712),* vol.I, Sada-A Coruña, 1998, 67–68.
17. See Bonet Correa, A., «Los tratados de montea . . . », *Figuras . . . ,* op. cit., 113–118.
18. See Taín Guzmán, M., *Domingo de Andrade . . . ,* op. cit., vol. I, 101–102.
19. See Fernández Gasalla, L., «Las bibliotecas de los arquitectos gallegos en el siglo XVII: los ejemplos de Francisco Dantas y Diego de Romay», *Museo de Pontevedra,* 1992, 344.
20. See Taín Guzmán, M., «El taller y la biblioteca del maestro de obras compostelano José de Seixas», *Cuadernos de Estudios Gallegos,* 1993–1994, 274.
21. See Folgar de la Calle, Mª. del C., «Un inventario de bienes de Fernando de Casas», *Cuadernos de Estudios Gallegos,* 1982, 543.
22. It is not clear wether the first volumen also belonged to Lucas (see Taín Guzmán, M., *El taller . . . ,* art. cit., 264,

note 10). In any case, their signatures are 23.588 and 23.589. The two books by Fray Manuel are RSE 1.097 and RSE 1.098.

23. It is *Varia Commensuracion para la escultura y arquitectura* by Juan de Arfe (see Pérez Costanti, P., *Diccionario de artistas que florecieron en Galicia durante los siglos XVI y XVII,* Santiago, 1930, 134).
24. There are *La aritmética práctica y especulativa* by Pérez de Moya and *La aritmética práctica* by Jerónimo Cortés (see Goy Diz, A., op. cit., 179 and 188.).
25. They are *La aritmética práctica y especulativa* by Pérez de Moya and *Elementos Geométricos de Euclides* by Luis Carducci (see Fernández Gasalla, L., art. cit., 332).
26. It is *Tratado de Geometria Practica y Speculativa* by Juan Pérez de Moya (ibidem, 344).
27. There are *Euclidis Elementorum* by Christophorus Clavius, *Triangulis Planis et Sphaericis* by Johannes Muller, *Problematum Astronomicorum et Geometricorum* by Daniel Santbech (see Taín Guzmán, M., *Domingo de Andrade . . . ,* vol. I, 41–45).
28. It is *La prospettiva* by Vignola (signature RSE 2.193 of the Biblioteca Xeral).
29. There are *Tratado de Geometria Practica y Speculativa* by Juan Pérez de Moya, *Libro de Aritmetica Especulativa y Practica intitulado El Dorado Contador* by Miguel Jerónimo de Santa Cruz, *Varia Commensuracion para la escultura y arquitectura* by Juan de Arfe, (see Folgar de la Calle, Mª. Del C., art. cit., 538, note 10, and 542).
30. Signature 1.292.
31. Signatures 2.015 and 2.016.
32. Signature 9.439 (I owe this information to Miguel Cajigal, to whom I wish to express my gratefulness). The book has the following ex libris: *«Franc. S. Mosquera Villamarín, presb. lucens. doct. compost. regal. consil. advocat. brigant. port. colegial eccles. princip. Dignit. etc. Han. MDCCCXXIV».*
33. With the ex libris: *«Çoy de Lucas Anttonio Ferro Caaveyro. Costtele 22 reales vellón».*
34. The ex libris of the first volume say: *«Este libro es usun de Fray Manuel de los Mártires, religioso lego, yjo del conbento de Nuestro Padre Santo Domingo de Santiago»* and *«Librería de Santo Domingo. Estante 30, Cajón 4º».* And the second says *«Estte libro es de Domingo Bugallo».*
35. Signature RSE. FOLL.-IV–6
36. In fact, the book has two ex libris: *«Librería de Santo Domingo de Santiago, Estante 30, Cajón 4º»* and *«Este libro es de Juan Anttonio Lezana, Año 1723».*
37. Signatures D556 and 4.640.
38. Signatures RSE 1.201, D559 and 10.711.
39. Signature RSE 4.081.
40. Signature 4.105.
41. With the title *«De la Arquitectura Civil»* (signatures RSE 2.424 and 17.537).
42. Signature R 4.334.
43. On the south wall of the southwest area there is what it looks like a carbon-pencil grid with drawings too faded to distinguish.
44. See Taín Guzmán, M., *Domingo de Andrade . . . ,* op. cit., vol. I, 189–191.
45. See Chamoso Lamas, M., «El claustro de la Catedral de Lugo», *Archivo Español de Arte,* 1940–1941, 133–137; Bonet Correa, A., *La arquitectura en Galicia durante el siglo XVII,* Madrid, 1984, 494–495.
46. See Rosende Valdés, A. A., «El Siglo XVI: Gótico y Renacimiento en la Catedral Compostelana», *Santiago, la Catedral y la Memoria del Arte,* Santiago, 2000, 154–156.
47. Its author is not clear although BONET Correa *(La arquitectura en Galicia . . . ,* op. cit., 496–500) suggests the name of Fray Gabriel de Casas. In any case, the façade was built from 1691 on by Pedro de Monteagudo (see Rodríguez Fraiz, A., *Canteiros e Artistas de Terra de Montes e Ribeiras do Lérez,* Pontevedra, 1982, 287–291). In 1708 they are still working on the interior vaults (see Sa Bravo, H. De, *El monasterio de Poyo,* León, 1985, 39).
48. The consagration was in 1803 (see Rosende Valdés, A. A., «Una muestra de arquitectura itinerante en Tuy: la capilla de San Telmo», *Actas del VI Congreso Español del Arte CEHA,* Los Caminos y el Arte, t.II, El Arte en los Caminos, Santiago, 1989, 271–283).
49. Ibidem, 272 and 276.
50. The rest of the lines corresponds to the other parts of the façade.
51. See Rosende Valdés, A. A., op. cit., 155.
52. See López Ferreiro, A., *Historia de la Santa A. M. Iglesia de Santiago de Compostela,* t. VIII, Santiago, 1906, t. IX, 38.
53. See Rosende Valdés, A.A., op. cit., 155.
54. See Martínez de Aranda, G. (1556–1620), *Cerramientos y Trazas de Montea,* Madrid, 1986, 159–161.
55. See Bonet Correa, A., *La arquitectura en Galicia . . . ,* op. cit., 103–104; Sa Bravo, H. de, El monasterio de Poyo, León, 1985, 28–31.
56. See Freire Tellado, M. J., «La construcción renacentista. Los trazados de montea bajo la escalera de los escolapios de Monforte de Lemos», *Lucus,* Boletín Informativo de la Excma. Diputación de Lugo, nº 42, sep. 1994, 59–65. This article was republished by the author, after a revision, with the title «Los trazados de montea de factura renacentista del edificio de los escolapios de Monforte de Lemos (Lugo)», *Actas del Segundo Congreso Nacional de Historia de la Construcción,* A Coruña, 22–24 de octubre de 1998, Madrid, 1998, 173–180.
57. See Bonet Correa, A., *La arquitectura en Galicia . . . ,* op. cit., 177–188; Lorenzana Lamelo, Mª. L., *Aportación documental al estudio histórico-artístico de dos fundaciones monfortinas: el Colegio de la Compañía y el Convento de las Clarisas,* Lugo, 1989, 53 on; Pérez

Rodríguez, F., «Algunas consideraciones sobre la construcción del Colegio de Nuestra Señora de la Antigua de Monforte de Lemos (Lugo), 1592–1619», *Actas del Simposium Monjes y Monasterios Españoles, Instituto Escurialense de Investigaciones Históricas y Artísticas,* vol. I, El Escorial, 1995, 495–521.

58. See Pérez Rodríguez, F., «Algunas consideraciones . . . », art. cit., 509.
59. See Freire Tellado, M. J., Los trazados de montea . . ., art. cit., 176–179.
60. See Chamoso Lamas, M., «El monasterio de Montederramo (Orense)», *Archivo Español de Arte,* 1947, 78–94; Bonet Correa, A., *La arquitectura en Galicia . . . ,* op. cit., 189–193; Ferro Couselo, J., «Las obras del convento e iglesia de Montederramo en los siglos XVI y XVII», Boletín Auriense, 1971, 145–177; Valle Pérez, J. C., *La arquitectura cisterciense en Galicia,* vol. I, La Coruña, 1982, 192–194.
61. Today the chapel houses the Cathedral's Museum.
62. Iglesias Almeida («La obra de un ribadaviense en la catedral de Tui», *Porta da Aira,* 1994–1995, 311) mistakes it with the present cross-vaulting of the building.
63. See Cendón Fernández, M., *La Catedral de Tuy en época medieval,* Poio, 83–85.
64. See Iglesias Almeida, E., «La obra de un ribadaviense . . .», art. cit., 311–312.
65. They were built between 1707 and 1711 (see Ávila y la Cueva, F., *Historia Civil y Eclesiástica de la Ciudad de Tuy y su Obispado,* t. IV, Os Bispos de Tui, Santiago, 1995, 308 (facsimile of the 1854 manuscript); Iglesias Almeida, E., *Arte y Artistas en la antigua Diócesis de Tui,* Tui, 1989, 103).
66. Freire Tellado (La construcción renacentista, art. cit.) looked up the sources of the drawing from Monforte in *Libro de Traças de Cortes de Piedra* by Vandelvira. See his explanations in «Capilla quadrada por arista» (fol. 80r.) and «Capilla por arista perlongada» (fol. 81r.). About the first type of vault see also Palacios, J. C., op. cit., 185–187.
67. On the topic see Rabasa Díaz, E., op. cit., 121–130 and 183–192.
68. See Vigo Trasancos, A., *La Catedral de Santiago y la Ilustración. Proyecto clásico y memoria histórica* (1757–1808), Madrid, 1999, 51–92.
69. In the times of Sa Bravo *(El monacato en Galicia,* vol. II, La Coruña, 1972, 94) it did not have the present balustrade and lacked some of the steps.
70. Compare both drawings on stone with the illustrations by Durero in *L'oeuvre gravé de Albrecht Dürer,* Paris, 1994 (first edition of 1980), 222, 223, 224, 225, 226, 227, 228, 231 and 232.
71. Compare both drawings on stone with the illustrations in Arfe, J. de, *Varia Commensuaración para la escultura y arquitectura,* Oviedo, 1977 (facsimile of the 1773 Madrid edition), pages 100, 103, 104, 105, 106, 117, 118, 165, 166, 168 and 169.
72. The chapter did not foster painting within the cathedral's workshop.
73. See Taín Guzmán, M., *Domingo de Andrade . . . ,* op. cit., vol.I, 353–375.
74. A.C.S., Varia, leg. 713, doc. 9.
75. A.C.S., Varia, leg. 713, doc. 17.
76. A.C.S., Varia, leg.713, doc. 83.
77. See Taín Guzmán, M., *Domingo de Andrade . . . ,* op. cit., vol. I, 357.
78. The same sculptor did the angels holding lamps and banners (ibidem, vol. I, 361 and 368).
79. A.C.S., Varia, leg. 713, doc. 19. We have documentation of the payment of the Virtues two years later (A.C.S., Libro 2º de Fábrica, leg. 534, fol. 223v.).
80. Unfortunately, the relocation of the floor ashlars in the two first cloisters has rearranged most of the existing drawings.
81. My work «Las monteas de la Catedral de Santiago de Compostela: de la arquitectura a la escultura» *(Actas del XIV Congreso Nacional del CEHA,* Málaga del 11 al 21 de septiembre del 2002, to be published in 2003) is devoted to that drawing on stone and the rest of the catedral's drawings.
82. See Ruiz de la Rosa, J. A., and Rodríguez Estévez, J.C., art. cit.
83. See Pinto, F., and Jiménez, A., art. cit., 80–81.
84. See Folgar de la Calle, Mª. del C., art. cit., 537; Fernández Álvarez, A., op. cit., 135, note 85, 267–282.
85. See Goy Diz, A., op. cit., 186.
86. See Fernández Gasalla, L., art. cit., 343.
87. See Folgar de la Calle, Mª. del C., art. cit., 541.
88. See Lorenzana Lamelo, Mª. L., op. cit., 56 and 58.
89. See GOY DIZ, A., «Los claustros benedictinos tras la reforma de los Reyes Católicos: noticias sobre su construcción y sobre sus programas decorativos», *Humanitas, Estudios en homenaxe ó Prof. Dr. Carlos Alonso del Real,* vol. II, Universidad de Santiago, 1996, 885.
90. Signature 24.732.
91. Signature 24.818.
92. Signature 23.578.
93. This information comes from Miguel Ángel Cajigal.
94. The authors Ruiz de la Rosa and Rodríguez Estévez (art. cit., 965–966) arrived to similar conclusions in their above cited article about the drawings on stone of the cathedral of Seville.

The vault of Arles City Hall: A carpentry outline for a stone vault?

Luc Tamboréro
Jöel Sakarovitch

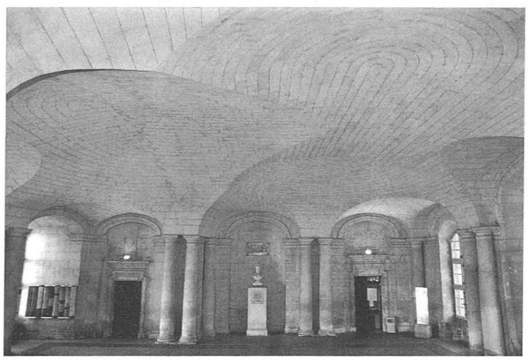
«Masterpiece of French stone-cutting» according to Pérouse de Montclos,[1] the vault covering the entrance hall of the City Hall of Arles is a true directory of the stereotomic virtuosity of the 17th century.

Yet the building work did not get off to a good start. When it had been underway for 6 and a half years, the defects left by the first contractors led to the decision on October 27th 1667 to demolish the building down to its foundations. But on August 7th 1672, the City Council decided *« . . . que l'hostel de ville de cette cité qui à esté demolly, comancé à estre rebasty et ensuitte redemolly sera incessamment rebasty jusques a son entiere perfection . . . »* The first foundation stone was laid on June 22nd 1673. The same day, Jules Hardouin-Mansart (1646–1708) arrived in Arles, on the invitation of the coadjutor to the City Archbishop's Palace, in order to give his opinion on the drawings prepared by Dominique Pilleporte, Master Stonemason, and Jacques Peytret, Master Painter.

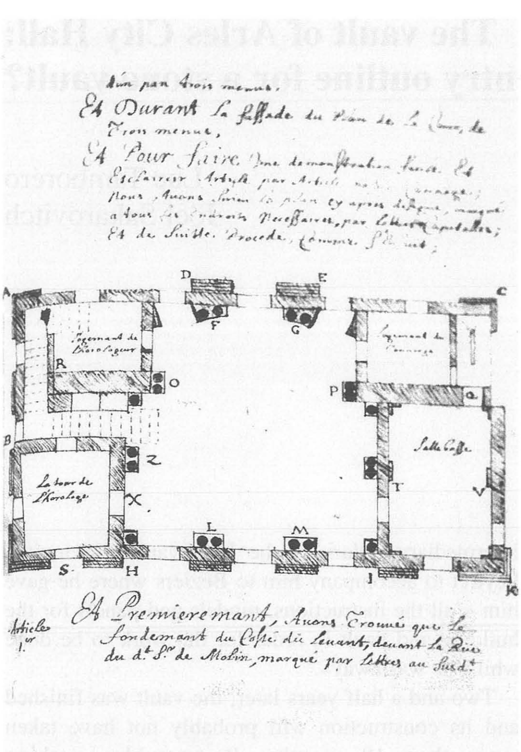
The Royal Architecture Academy was then two years old and Hardouin-Mansart 27 years old. For 6 years, he had been managing a small team which Jean Boyer called the «Mansart Agency».[2] The team included, among others, his brother, Michel Hardouin-Mansart, who accompanied and assisted him in Arles, and his brother-in-law, Robert de Cotte. It was on the occasion of the June 1673 visit that Hardouin-Mansart drew a sketch (which has disappeared today) in which he erased the intermediary pillars of the Hall vault. He invited Peytret to accompany him to Beziers where he gave him « all the instructions, models and panels for the building and vault in order for the work to be done whilst he was away».[3]

Two and a half years later, the vault was finished and its construction will probably not have taken more than 18 months. It resembles nothing previously known. Covering a square of approximately 16 meters, its arrow is only 2,40 meters high. At first glance, it can be described as being composed of two oval vaults penetrating each other crosswise and sustained by lunettes (photographs 1 and 2, and figure 5).

Whilst the vault of Arles has been studied frequently, it seems that no study precisely accounts for its shape



Photograph 1



Photographs 2

nor for its construction. The rapidity with which it was built plus the apparent complexity of the penetrations and the subjacent line seem inconsistent with the shortness of the presence of Mansart on site. Mansart taught Peytret in less than a month how to conduct the work. We can question how a man, originally a painter, and although he had some knowledge of the geometrical needs of his trade, could claim in such a short period of time to be able to manage the drawing, the manufacturing and the construction of such a complex vault. The answers to these questions lie in the analysis of the construction and in the reconstruction of the steps from the design stage to the cpmpleted vault.

Our working method

The working method which has been followed is based on historic study principally of the archives, a precise record and the creation of a model on a scale of 1/5.

Thanks to the numerous accounting archives of the City Hall, we were lucky to be able to piece together with considerable precision the progress of the work. Purchase orders,[4] as well as documents discussing the resistance of the building were kept. It is important to note that the lack of reference to reinforcement or the purchasing of iron enables us to eliminate the presence of iron ties inside the vault. Part of the archives was published by Jean Boyer in 1969.[5] Furthermore, the vault has been the subject matter of various unpublished studies by Emile Fassin, at the end of the 19th century,[6] and numerous publications during the 19th as well as 20th centuries.[7]

The precise and complete survey of the volume and of each soffit which was carried out in 2001 has been cross-checked with the photogrammetric survey implemented for the Regional Board for Cultural Affairs and the Regional Council for Inventory. This survey confirmed that « La Canne d'Arles», which was a measurement unit at the time, was 204,6 cm.[8] The «Canne» was divided into 8 «pans» of 25,6 cm which were divided into 8 «menus» of 3,2 cm divided in turn into 8 «lignes» of 0,4 cm. The fact that the vault had been rigorously built according to a module is confirmed by the survey of the columns. Indeed, the vault rests on 20 Roman Doric columns without pedestals. The module of the columns is of 1 pan. A column is divided into 16 modules of 1 pan of the height which is 2 «cannes» high that is 409,25 cm.[9] Given the exactness of the dimensions measured in 2001, it seems that the decisions taken by the Council regarding the requirement of high quality work had been respected during the construction.[10]

As is the case for the vault, the model, made by Luc Tamborero for his Masterpiece for the Stonecarvers Corporation[11], has been made in Fontvieille stone.[12] Its construction, step by step, was the best way to test the efficiency of the various hypotheses of how work was carried out.

The construction of the vault

We believe that the construction of the vault was based on 3 points:

— the regulatory lay out
— the double role of the plan view
— the stereotomy and its methods

The regulatory lay out

Two interpretative frameworks are superimposed on the setting up of the vault. The first one is linked to the module of the «canne». For instance (Fig. 1), the base square is 8 «cannes» (16,37 m) long on the side, and the columns for the north and south walls are regularly spaced with regard to this unit of measurement (Fig. 2). The second framework concerns the construction of the regular pentagon, which does not touch the circle, given by Dürer[13] (fig. 1 to 4).[14] It enables one to determine the position of the east and west columns, of the key stones and of the centering point, as well as the posotion of the penetrations and even the arrows of the arches as we will demonstrate below. The second implementations are of course incommensurate with the «canne».

The drawing of the North-East and North-West twin lunettes clearly confirms the existence of these two frameworks. Indeed, the axial edge, for example, of the North-East lunette joins the middle 2 of the penetration edge with point 1 (Fig. 5). The drawing of this edge, which rests partly on the modular drawing and partly on the pentagonal drawing, is therefore not orthogonal to the penetration edge. This remark proves that the regulatory drawing has been scrupulously followed.

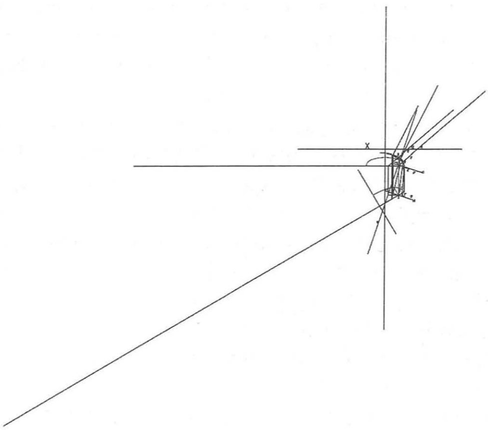


Figure 1
Drawing of a circle and semi-circle, intersecting according to a bowstring equal to their common radius. The point A and A′ will be the horizontal projections of the keys of the large vault semidomes

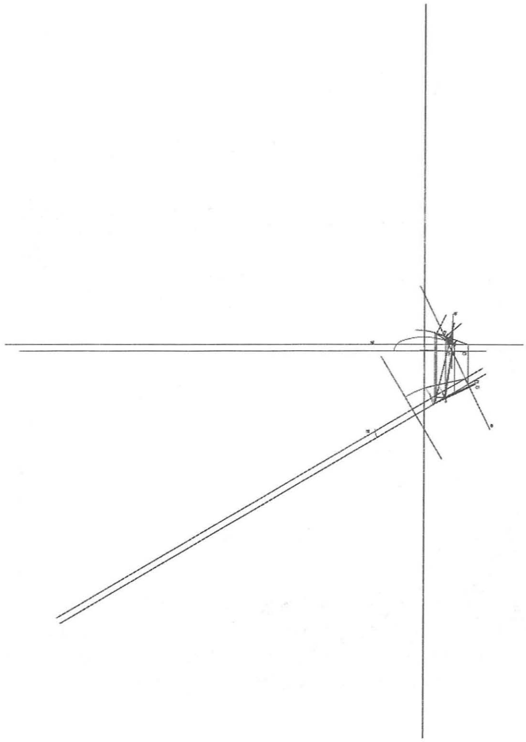


Figure 2
Construction of the regular pentagon which does not touch the circle, given by Dürer, construction referred to as «with constant opening» (the side of the pentagon is the radius of the circle of figure 1)

The double role of the plan view and the volume defined according to the penetrations

One of the principles of constructing the drawing apparently lies in the establishment of the horizontal projections of the penetrations. The penetrations of the large and small vault with the twin lunettes are flat; that of the two main vaults is partially flat; those of the entrance lunettes with the principal vaults are circular (horizontal projection).

We have chosen to work on the small vault, the construction principle being identical to the large one.

Once the plan implementation had been determined, the penetration edges between the vault and the lunettes were drawn on this very same projection. These edges, which are basket-handles with 5 centers whose span is

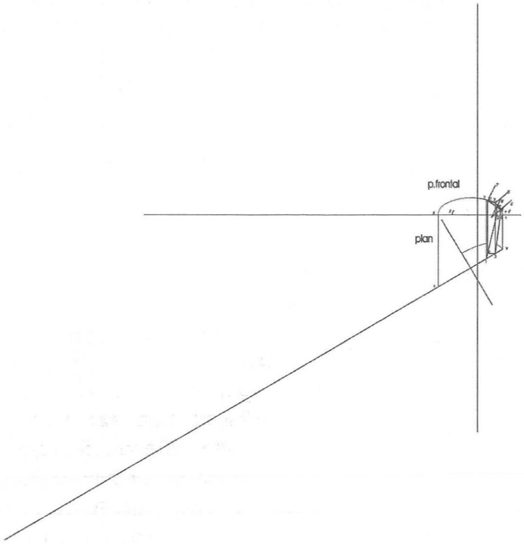


Figure 3
The two segments [x,y] and [x′,y′] are the layout of the penetrations of the two twin lunettes in the half semidomes of the small vault. This drawing was obtained from a modular North-South layout and of a pentagonal East-West layout

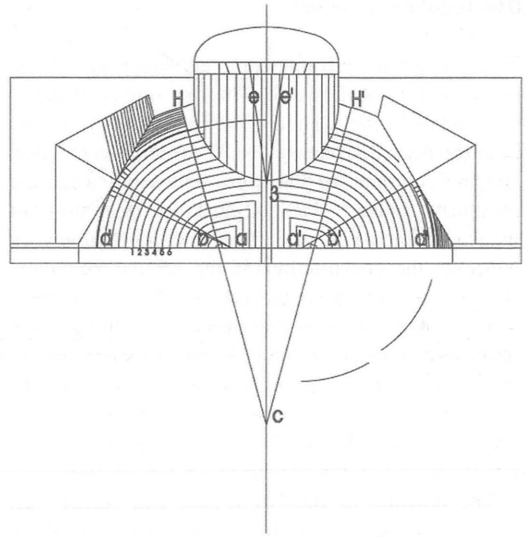


Figure 4
The axes of the twin lunettes are extended until they intersect (a and a′) with the straight line of the top B and B' of the pentagon.
The sides B• and B′• cut C and C' the spacing AA′.. The segment CC′ is located at 10 cm above the base square according to the regulator drawing, 3 cm according to the tracing; taking into account the encounter angle and the number of previous operations, the mistake is minor. From c, in the middle of AA′, we draw cC and cC′ which cut BB′ respectively at b and b′. The points a and b will be the centering points of future drawings (fig 6 and after). The point 0, which positions a couple of columns, is the middle of segment 1,1′ and does not belong to the straight line AA′.

given, have been drawn following the method of C Huygens (1629–1695). But contrary to Huygens who considers that the arrow is given and chooses the first centering point, Mansart gave himself the two centering points (one of which is point a) and deduced the arrow from those[15] (Fig. 6). All plan, penetrations or outline arches are basket-handles with 5 centers, drawn according to the same method. Only the large arch which supports the partition wall and on which the two vaults rest, is a connection arch with 3 centers. Moreover, the global drawing is based on a template shape arch included in the vertical plan bH. The distance bH being unequal to the distance bK, the two arches are different. But whereas a regular distortion from bK to bH would have produced horizontal joints, Mansart chose two different connection curves which generate the bending of the intrados.

The order of the drawing and of the construction is therefore as follows:

— the periphery arches and the twin lunettes
— the large arch
— the small vault with the large entrance lunette
— the large vault

The archives also confirm this order.[16]

The rest of the drawing (Figs. 7 to 10) will be obtained by permanent back and forth between the horizontal projection and the beads, on this view of the different arches. As the Penetration arches for the vault and the lunettes have alreadsy been determined, the drawing of the large arch and the drawing of the template shape arch bH are deduced from them (and not the contrary). The five centering points a, a′, b, b′,c, enable one first of all to draw the curve (d-d′), tangential to the lunettes (Fig. 7). The center «a» is used for transporting the shape of arch I to the cross

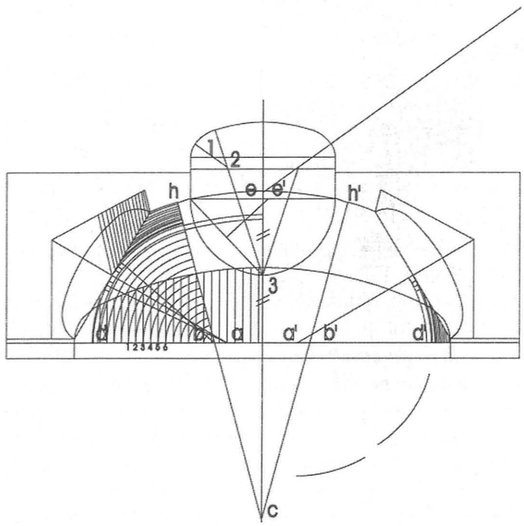


Figure 5
The plan view with its six centering points which will be used both for the horizontal projection and for the elevation of the arches

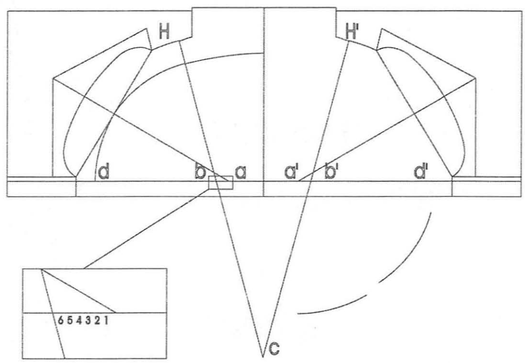


Figure 7
The curve (d-d′) created by the five centering points a, a′,b,b′, tangent to the lunettes, is a curve of rotation; the joint curves distort themselves into curves with three centers b,b′,c. For a five-centers-curve to evolve into a three-center-curve, the angular part which will disappear has to be fragmented into several centering points, in this case into 7 parts

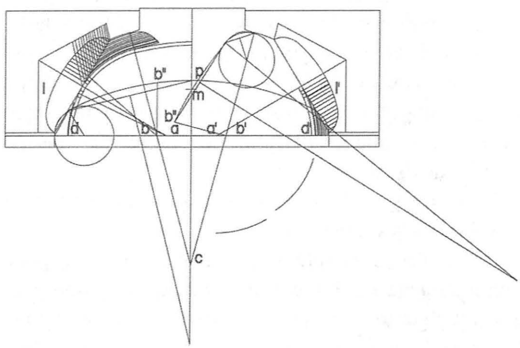


Figure 6
The centering points a and a′ are two of the centres of the basket-handles with 5 centres. The first centre (i) has been made by a transfer of dimensions with a compass, the last centering point is (a), the second centering point (j) is deduced from it

wall, the center «b» is used for transporting the shape of arch I to the template arch bH (Fig. 8). It is the distortion of the crosswall springing curves which confirms that the order which is followed is indeed the one which has been described. This arch is composed of two distortion curves and a connection arch which is the only one to be divided regularly into 45 modules. These modules will generate the disposition of the joints on the small and the large arch.

As the first element of the vault to be constructed, the works for the partition arch began on October 24th 1674; the key of this arch is located at the same level as the top of the large vault. The arch is already built, with an arrow whose length is one «canne» and one «pan» and a half. (243 cm, point p on fig 8) when the model is received at the beginning of November from Paris[17]. Mansart wanted the height of the arrow to be one « pan» and a half less (204,6cms, point m on Fig. 8). After a quick discussion, it was decided to leave the arch as it was and to carry on the works.[18]

The construction of the arch of the main entrance and of its penetration in the small oval vault, which had been drawn with ruler and compass, followed the same procedure described above (Figs. 9 and 10). It is important to note that the joint lines do not turn back on the penetration edge.

This fact shows that the respect of the module on the lunette, as well as the esthetic concern about the

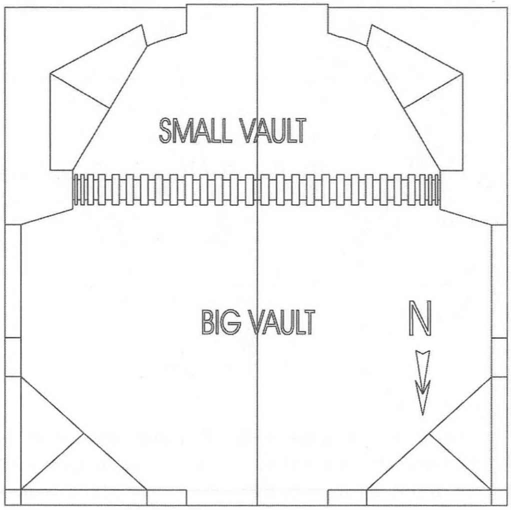


Figure 8
From the starting point of the arches (I-I′) to the curve (d-d′), the centers a,a′,b,b′ generate the distortion. It is the volume of the vault and not the volume of the lunettes which is defined. The connection, from the top of the distortion to the chosen height of the large arch, is done through the tangency to the nearer circle and the connection whose top is located at b″ is drawn the same way. On the large arch, the connection curve is divided into 45 modules. We can already begin to understand the magnitude of the difficulty. First of all, the modules are future arch stones burred on the segment crossing through aa′.
With plan view, the models represent the soffits and joint lines determined by their rotation according to their respective evolutive centering points (fig. 7) which therefore creates 8 irregular soffits. Secondly, the connection curves previously drawn not being identical, the soffits are not on the same level; there is a 5 cm difference for a rotation of 4 meters. Thirdly, the stones of the penetration arches have a soffit in the direction of the lunettes, the other one in the direction of the ray of the vault

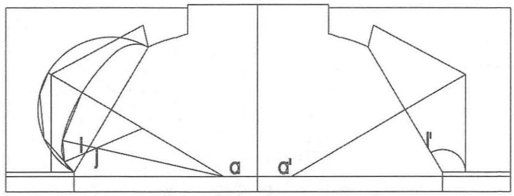


Figure 9
The construction of the arch of the main entrance and of the penetration of the small vault.
The penetration is drawn from the two centering point e and e′. The soffits, in plan view, starting from [c-h], [c-h′] extended by the center c and made to encounter the soffits of the lunette. In the aim of having a module almost regular on the penetration surface and constrained by the forms and penetrations drawn using ruler and compass, the draughtsman has chosen to skip some rows. two lunettes rows penetrate twice on the row into one vault row. Along the same joint, approximately 2 meters, the level difference is 7 cm maximum

penetration curve, outweighed the definition of the volume. This was therefore apparently not defined.

The compliance of this drawing with the survey is also proof of the previous hypothesis.

The stereotomy and its methods

A number of different cutting techniques were certainly used for the construction of this vault.

The first two rows, which are part of the outside wall (and which therefore would have been construcred first) are corbelled and therefore have been square cut. The two semidomes of the large vault, which follow surfaces of revolution, were probably cut by panel according to the truncated cones method which was very classic at the time. However, on the small vault, the semidomes are not regular as mentioned earlier.

It is likely that the arch stones of the 6 rows of evolution were square cut.

It is also probable that, in view of the good implementation of the joint curves, the vault was constructed on a «veau», the curve of an arch with a plastered surface where the joint curves were reported.

However, as far as the arch stones of the lunettes are concerned, a square cut seems impossible for the following reasons:

— the archives mention the fact that Mansart « *baillera le trait à celui qui le conduira*» (will teach to whoever carries out the work) and Peytret spent approximately one month to receive « *les instructions modèles et panneaux pour lesdits bâtiment et voûtes*»[19] (the model instructions and panels for the building and

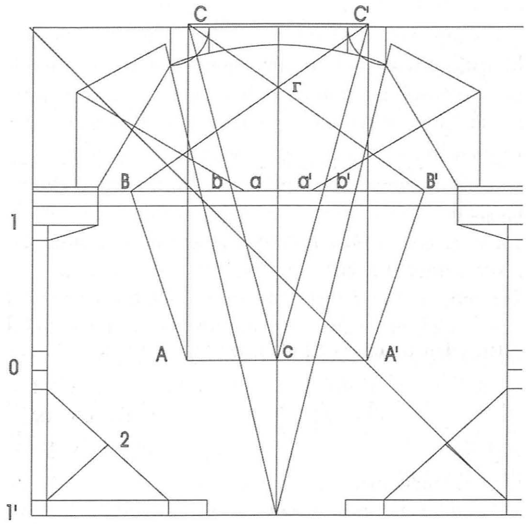


Figure 10
We can observe that the platband is treated separately from the vault drawing: the centering point is located at a distance of three alf span under the springing of the arch. Although this point is located at approximately 10 cm from point 3, the draughtsman did not get them mixed up

Example of a drawing on a twin lunette

vaults). It is sure that Peytret did not need a month of apprenticeship with the master in order to use the square cut technique.

— a model was made out of wood for the large lunette, thereby also suggesting the use of a more complex method than the square cut.
— we know that the square cut was not the method advocated by the Academy and Mansart, less than any other, would have pushed for its use.
— and last but not least, square cut consumes a huge quantity of stone at the level of the reins of the vault, especially with the curved penetrations and for a vault of at least 50 cm thick.

The square cut is therefore excluded for the lunettes. But a traditional cutting by panel does not seem appropriate either. Indeed all the intrados are warped, which eliminates the (numerous) drawings out of a flat intrados panel.

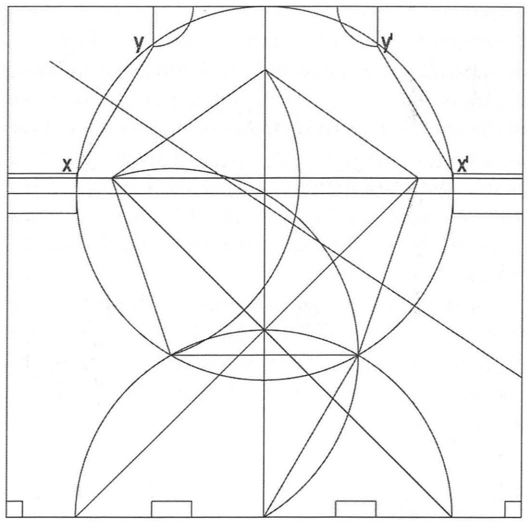


Figure 11
Head angles
The lunette is defined by the arches xy and zt whose elevations are turned down on the plan. The arch xy projects itself into frontal x′y′. Any soffit is given through its plan 1–2–3–4. In terms of carpentry, the frontal plan is «la herse» and the horizontal plan is «le plan». The segment [3c] is a borrowed chevron, that is a construction line which is not the outline of the piece but a marker for manufacturing. It is parallel to the frontal plan. The straight line 6′–4′ goes through one of the centers of arch zt. It enables the definition of the joint plan of the arch stone: it is enough to consider a parallel line 3′–5′ through the frontal plan 3c . In the same way, we can define the other side of the joint 8′–2′–1′–7′. The angles which are necessary for the cutting appear on the frontal projection and will be transfered through the bevel square.

Moreover, the panel method requires different panels for each arch stone, given the irregularity of the arch stones on a same row and in between rows. This time consuming drawing does not seem to be compatible with the swiftness of the work nor with the archives which state a limited number of patterns for the panels.[20]

This is the reason why we think that the «méthode à la sauterelle»(bevel square method) cutting method was used. Used in carpentry, this was a quick method for cutting arch stones, using simple angle transfers and without the need for drawing all the panels. The principle is as follows: to determine a polyhedron

with 6 sides, it is necessary, for each crown, to know the angles of the edges which converge to it. Here one of the sides is warped but the knowledge of those angles is sufficient for the cutting. Starting from one of the joint plans, two segments of straight lines of the intrados (or «soffit») —non coplanar segments— will enable the «adjustment», during the cutting, of the intrados surface. Figures 11, 12, and 13 show respectively the drawing of the angles needed for the construction.

For the penetration arch stones, the X plan is used (Figure 12) on which the panel of the horizontal projection is applied. The penetration can be square cut since the radial joints of the small vault are vertical.

Conclusion

«We must hear that architecture will come out soon, as we say, from the trowel and the rubbish of bad interest, and that working only for glory, it will create works which will make most of the works created in the past unbearable to be seen».[21] The vault of the City of Hall of Arles is certainly an illustration of this quotation from Blondel. «Working only for glory», Mansart did not ask for any money for his own work and it was on his initiative that the City of Arles paid the architect.[22] As for the « trowel architecture», the vault surely works on it. We perceive the penetrations and the geometrical volumes to be regular whereas there is a profusion of warped surfaces. Mansart's constructive willingness is based on reversing the usual order of choices. He first decided on the drawing of the penetration edges which are to the eyes more pregnant than the shape of the volume themselves. We could conclude that his esthetic choices took priority over his constructive choices. But the strength of Mansart in this work was to offer simultaneously a cutting method which would allow the execution.

He therefore became the best representative of the young Architecture Royal Academy by breaking away from the usual models, linking technique innovation and formal imagination.[23]

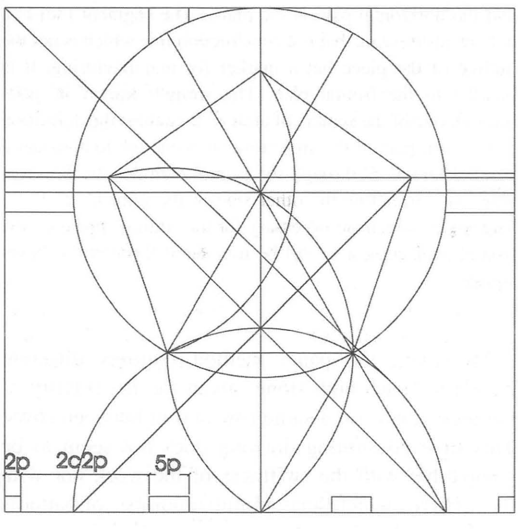


Figure 12
Joint angles
One can burr down on the horizontal plan the joint panel (6′–4′–3′– 5′) and deduct from it the joint angles.
On the figure, the horizontal plan X is also mentioned; the distance report 3′–x2 and 4'–x1 allows to find the X plan on the stone and to square cut the penetration.

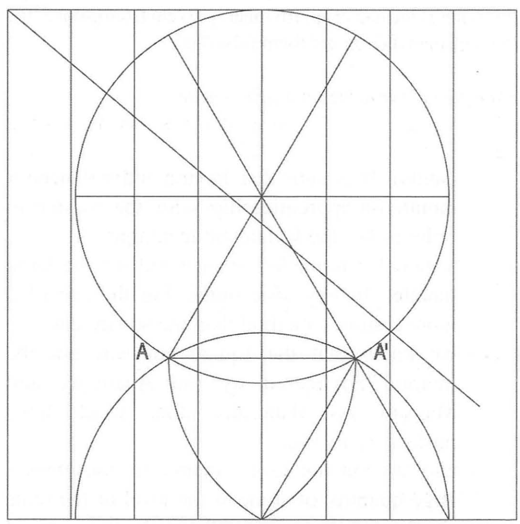


Figure 13
Soffit angles.
One can burr down around the horizontal hinge (for instance the one which goes through point 3) the plan defined by the two straight lines 3–4 and 3–c to obtain the real size of this angle. In the same way, we can determine the angle for the two straight lines 3–4 and 2–4 thanks to a hinge going by 4. A distance report on segments 3–c and 2–4 determine the second edge of the soffit.

Constructed	Bridge	Location	Span I of the largest arch [m]	Rise h [m]	Rise ratio h/l 1 over
595–605	Zhaozhou Brücke (An Ji, Anji)	Provinz Hebei	37,02	7,23	5,12
1341–1345	Ponte Vecchio	Florenz	30	4,4	6,82
1499–1500	Ponte degli Alidosi	Castel deI Rio	42,17	19	2,22
1556–1566	Stari Most	Mostar	28,69	12,02	2,39
1567–1569	Ponte Santa Trinita	Florenz	32	4,57	7,00
1588–1592	Ponte Rialto	Venedig	28,8	6,4	4,50
1595–1598	Fleischbrücke	Nürnberg	27	4,2	6,43

Rise-span ratios. Data from different sources vary, see also http://www.structurae.de

NOTES

1. Pérouse DeMontclos, Jean-Marie (1983).
2. Boyer, Jean (1969).
3. Boyer, op. cit., p. 25.
4. The lines to draw the working drawing, the number of panels for cutting, the lead for the columns, etc. are clearly mentioned.
5. Boyer, Jean. Op. cit.
6. Fassin Fund, (ms2412).
7. Cf. in particular Pérouse de Montclos, Jean-Marie, op. cit.
8. According to Fassin , ms 2411, according to the index of ancient measurement units of the City of Arles dating from 1897, one canne d'Arles = 204.72 cm. In the ms 2412, « A qui revient l'honneur . . . », one canne d'Arles = 204.40 cm, p. 92.
9. Cf. archives in Jean Boyer, op. cit, p. 28. The current concrete ground diminishes slightly (approx. 1 cm) this dimension.
10. For instance the 128 cm-wide spring-mattresses correspond to 5 pans (5 pans = 127.89 cm), or the width of the 51,10 cm columns corresponds to 2 pans (2 pans = 51.15 cm).
11. Association Ouvrière des Compagnons du Devoir du Tour de France.
12. The stone was provided by Les Carrières de Provence at Fontvieille. Study time 1000h, Creation time 800h.
13. For this drawing, see : Peiffer, Jeanne (1995), pp. 208 and 369.
14. In order to facilitate the reading of the diagrams, the construction lines presented, to start with, as full lines will then be dotted and then eliminated in further figures if no longer needed.
15. *Encyclopédie des métiers, La maçonnerie et la taille de pierre*, Tome 3, fascicule 2, p. 61.
16. Jean Boyer, op. cit, p. 27.
17. Executed by the wood worker Fontvieille, according to Boyer, Jean, op. cit.
18. Debate related in the deliberations on November 3rd 1674, Boyer, Jean, op. cit. p. 30.
19. Jean Boyer, op. cit, p. 25 et 27.
20. 11 patterns for the whole vault . . .
21. Blondel (1673).
22. His payment was £500; his annual salary at the time was £6500, whereas Peytret was paid £135 for three months of wages.
23. Regarding the use of geometric knowledge in the setting up of the architect trade, see Christele Assegond.(2002).

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Palladio's timber bridges

Gennaro Tampone
Francesca Funis

Andrea Palladio, in his Treatise «*I quattro libri dell'Architettura*» (1570), after a short introduction on timber bridges containing general indications on their planning, presents the bridge on the Rhine, Figure 1, ordered and described by Caius Julius Caesar in the *Commentarii* of the Gallic war, as a model from the classical antiquity; of this work and of its structure Palladio also presents, with text and drawings, a personal interpretation that he calls inventione», elaborated in his youth as he says.

In subsequent pages of the Treatise, he describes a few timber bridges of his own «invention».[1]

Of the bridges represented in figures 2 through 6, only the Cismon river bridge, Figure 3, the Brenta bridge in Bassano, with a covered road, Figure 2, and the Bacchiglione bridge in Vicenza (a work which was planned following Palladio's interpretation of Caesar's Bridge and was considered an experiment) are ever actually built, according to a contemporary witness;[2] on the latter only a few written references remain (Palladio, Scamozzi). The Bassano bridge, probably the most famous, has been destroyed many times and rebuilt in accordance to the original specifications. In his Treatise, Palladio presents three more *inventioni* of great interest but without reference to a particular location or situation.

The Caesar's bridge interpretation matches the palladian restoration of the remains of the Titus arch in Rome, one of the more philologically correct and certainly, amongst the several available drawings

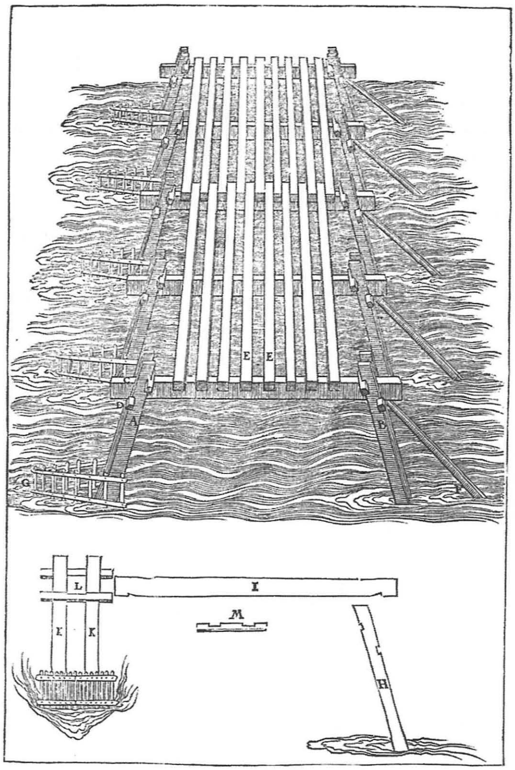

Figure 1
The bridge on the Rhine in the interpretation of Andrea Palladio. Palladio 1570. 3: 14

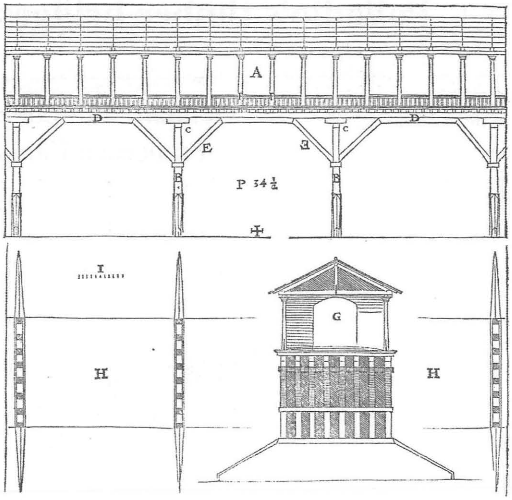

Figure 2
The Brenta bridge in Bassano. Palladio 1570. 3: 20

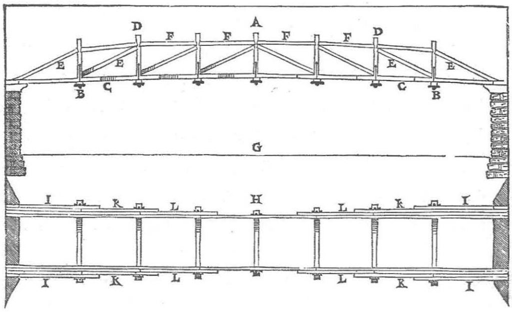

Figure 4
Drawing of the «*prima inventione*». Palladio 1570. 3: 17

elaborated by other Authors, the closest to the original features of the monument as the excavations and investigations carried out in Rome in the beginning of the XIX c. by Raffaello Stern and Giuseppe Valadier demonstrated.

The whole set of bridges, whether built or only described, presents an outstanding interest. The Cismon river bridge and the first invention can be assumed, to a certain extent, as the most representative of the palladian technology on the subject and of the advances achieved by Palladio.

The term «invenzione», from the Latin «*invenio*» (to find, discover, invent, device etc.) means, in general, to achieve a discovery, or, a contrivance. For Palladio, «invention» also means a building, realized or just simply planned; a fruit of a very personal and original elaboration, different from anything seen up to date. In the eighth chapter of Book II, Palladio maintains that, Palladio maintains that he intended the Treatise to be a collection of drawings of «quelle fabbriche, le quali overo fossero compiute, overo cominciate, e ridotte a termine che presto se ne potesse sperare il compimento: ma conoscendo il più delle volte avvenire, che sia di bisogno accomandarsi a i siti, perché non sempre si fabbrica in luoghi aperti, mi sono poi persuaso non dover esser fuori del nostro proposito, lo aggiungnere à disegni posti di sopra alcune poche invenzioni fatte da me, a requisizione di diversi Gentiluomini, le quali essi poi non hanno eseguito».[3] Invention is, in the Palladio's writings, also «interpretation» of an ancient literary text, such as Caesar's description of the bridge on the Rhine river. In the case of the bridges, the term invention connotes an idea which is original, never before seen.

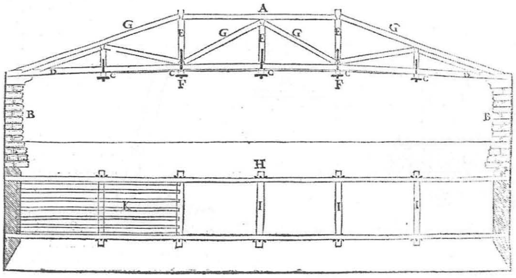

Figure 3
The Cismon river bridge. Palladio 1570. 3: 15

Inventione, for Palladio, is also a model, something (an idea, an interpretation of architecture, an architectural type, a mechanical device for the construction etc., expressed by a literary description, a maquette or simply a set of drawings) which is new and original but independent from contingent situations and can be applied when the general situations occur.

To this purpose it is interesting to note that Palladio, as his contemporaries, thought that it is

possible to extend with no limits the span of the bridges in general and of his owns in particular, only increasing, in a proportional way, the dimensions of the parts; a conviction that Galilei was able to demonstrate not true for the arithmetic *ratio* of the dimensions and possible only to a limited extent.

An interesting comparison can be made to the french contemporary architect Philibert de l'Orme, who also uses the word *invention* in his Treatise *Nouvelles inventions pour bien bastir et a petit frais* (1561). The meaning of the term, applied mainly to the light timber vaults made with boards centrings, first described by Vitruvius as the *concamerationes*, is certainly closer to the today's one because the Author proposes, with several examples, many detailed configurations and possibilities for making easy and inexpensive coverings of very fashionable spatial shape.

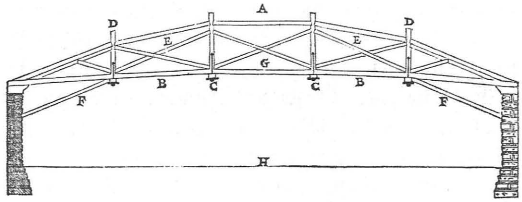

Figure 5
Drawing of the «*seconda inventione*». Palladio 1570. 3: 17

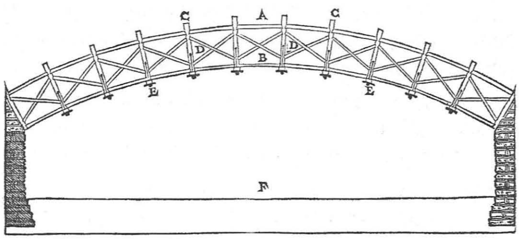

Figure 6
Drawing of the «*terza inventione*». Palladio 1570. 3: 18

Advances in bridge design

The technology of planning and building bridges are presented in the Treatise as a continuity and, at the same time, as advances of the roman technology of a highly significant period, the passage from the end of the first century b.C. and the beginning of the following, i.e. at the Vitruvius's time.

Palladio knew well both the *Commentarii* by Julius Caesar, that he read in his youth, and the *De Architectura* by Vitruvius (a handbook for the architects but more an ideological source for every cultivated man of the Renaissance) especially because he had prepared xylographic drawings for the editions of the two works (Venezia, Marcolini, 1556 and Venezia, De Franceschi, 1567) cared by the learned Daniele Barbaro, the Patriarch of Aquileia, also the appointed Historian of the Venetian Republic.

Mainstone[4] noted that the drawings of the timber bridges of the Treatise are «the first surviving fully detailed designs for bridge trusses»; it is anyhow important to observe that still they are schematic, affected with omissions of some peculiar details which are essential for their full understanding.[5]

The substantial Palladio's contribution to the understanding of the bridge on the Rhine is the interpretation of the joints, which were connected by means of the *fibulae* (buckles), connectors of which he proposes the design (made of timber?), and therefore the interpretation of the clever way in which the bridge is progressively built and assembled. It is worth noting that the other Authors who tried to give interpretation of the classical text[6] generally designed the *fibulae* as rope bindings: these are absolutely different from the Latin word and far from its peculiarity, in any case, not really efficient in such a work; certainly too rough and primitive to meet the Caesar's requirements of dignity.

One more concept is assumed as fundamental by Palladio, this is that with the adopted configuration and, more specifically, the designed joints, the more the bridge is solicited by the stream and the loads, the more its stability is increased because the parts get tighter and the work is made firm. In the Palladio's drawings no bracings, as usual, are present.

In the description of his personal inventions, Palladio strictly follows the same Caesar's exposition scheme, the same style, concise and effective, essentially explaining the characteristics of the river (the parameters are the breadth, the height of the banks, the speed of the stream), showing the disposition and the dimensions of the members, the building process, the invention of the special connection device etc.; the

terms employed are the same too, of course translated in *Volgare* from Latin, as for instance the «natura del ponte», the «fermezza dell'opera» (*operis firmitudo*).

With the said similarities Palladio starts, on the ideal and practical level, a personal continuity with the great classical technology expressed by one of the most celebrated engineering work; but this is also a way to legitimate his work trough the authority of the *Commentarii*'s Writer and the occasion to show the advances he was and is able to achieve.

The most important advance is the fact that his bridges are made «senza porre altrimenti pali nel fiume», that means structures without intermediate supports, conceived with the purpose of avoiding damages to the piers caused by floating trees shafts, violence of the stream, vessels. The same span, 100 feet of Vicenza (36 m about) for the Cismon river bridge, is exceptional; there is only the witness of the Trajans bridge at Drobeta, planned by Apollodorus from Damascus, long more than 1100 m, on 20 piers large 18,5 m and then each bay reaching a span of almost 33 m. On this fantastic achievement (103–109 a.D.) it is important to note that each bay benefits of the continuity with the adjacent ones, each end of the bay can be considered with fixed joints, a relevant advantage for both strength and stability. Reproduced in bas relief on the Trajan Column in Rome, Figure 7, it constituted later the obliged reference for many bridges such as, for instance, the famous Ironbridge on the Severn, Shropshire, in 1779, which is designed with a very similar structure of cast iron, the first structure of this material.

Figure 7
Trajans bridge planned by Apollodorus from Damascus, reproduced in bas-relief on the Trajan Column in Rome

The Caesar's bridge (which can be considered directly inspired by the pontoon-bridges in spite of the intentions to do something different for the dignity of the Commander and of the Roman nation), composed as it is by a certain number of piers at a distance that we can estimate not exceeding 10 metres (about 30 feet) and, in a similar way, the Trajan's bridge, being modular, have the advantage to be extendible with no limitations.

The Palladio's configuration of his timber bridges is quite different in comparison with the others mentioned. It is based on the use of a net of triangular meshes which is not deformable if the three sides are rigid rulers.

The use of the triangle in architecture is to be considered quite ancient if one only recalls the roofs profile of the buildings and the pediment of the classical architecture. But the theorization of the properties of it in the building technique is due to Leonardo da Vinci,[7] Figure 8; we can assume, however, that Palladio did not know the Leonardo's writings on the subject.

The palladian bridge structures can be considered lattice girders, certainly amongst the first employed with a consciousness of the benefits they can give —strength, minimal weight, attitude to keep the shape etc.— and systematically adopted. In the

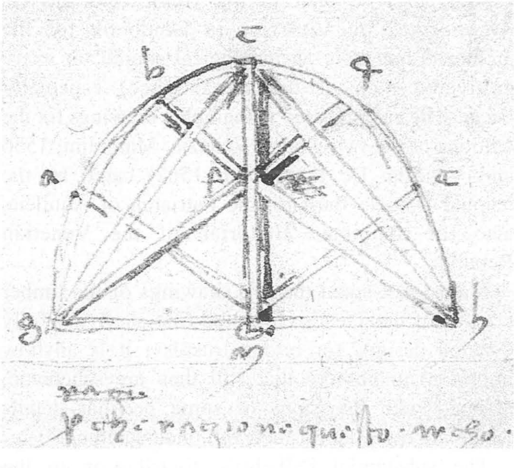

Figure 8
The theory of the «not deformability of the triangle» by Leonardo da Vinci. Leonardo da Vinci. 1987. Manoscritto B. 19v

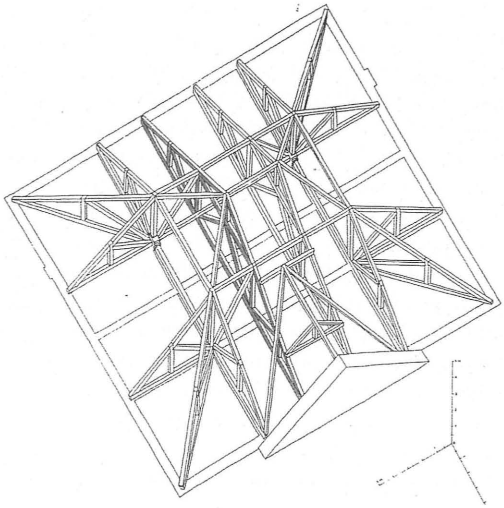

Figure 16
Trusses in the palladian villa Emo in Fanzolo. Drawing by Bordignon Favero, G. 1970

Palladian structures, every member is essential up to the point that if one of them is subtracted, the structure fails; besides, because these structures are made of timber, the joints can be considered, at least to a certain extent, hinges. Essential to note that in the Leonardo's drawings as in the Contemporaries to them, the timber structures are generally redundant as for the number of rulers, in the attempt to make them not deformable, therefore really hyperstatic.

The structural configurations of the palladian bridges, i.e. the shape of the structures, originate straight from the trusses. It is clearly so, for instance, for the Cismon river bridge, a direct proliferation of a classical truss[8] (see for istance the palladian villa Emo's trusses, Figure 16, 17). Both concepts of triangular mesh and truss as an elementary structure expansible are to be recognized in the current realizations of the XV and XVI c. in Italy and in the drawings and works by Simone del Pollaiolo detto il Cronaca, Sebastiano Serlio, Giuliano da Sangallo il Giovane, Giorgio Vasari and Others; but in the palladian proposals there is much more of rationality.

The cord of the Cismon river bridge and of the first invention has a slight rise, an original and advanced feature for generating favourable auto-tensions

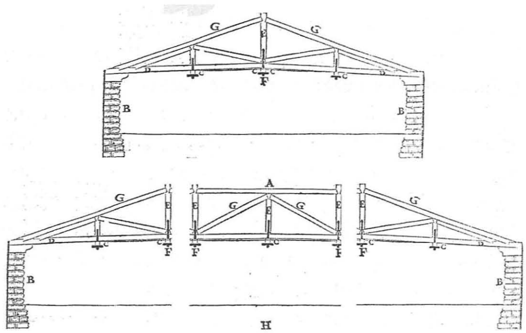

Figure 17
The origin of palladian bridges' structural configurations straight from the trusses

during working of the structure; the whole mechanism becomes active due to the presence of this sophisticated arrangement. The rise is also present in the first invention and, of course, in the second and the third. This too is an important palladian invention. The timber palladian bridges are, in a way, arches, especially in consideration of the fact that also the extradox is shaped as an arch (portione di cerchio minor di mezzo circolo).

A few built-up beams designed by Leonardo show, incidentally, a rise;[9] the Polonceau Truss (1839) too has a rise.

Funis, the first to notice a double line (which was omitted in the late editions of the Treatise, also in the Carampello edition, 1581, Figure 9, but not in the english edition, 1738) at the intradox of the front view of the Cismon bridge, interprets this line, together

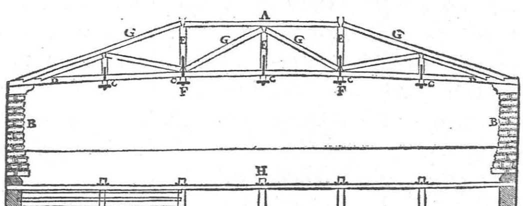

Figure 9
The Cismon river bridge. Palladio 1581. 3: 15

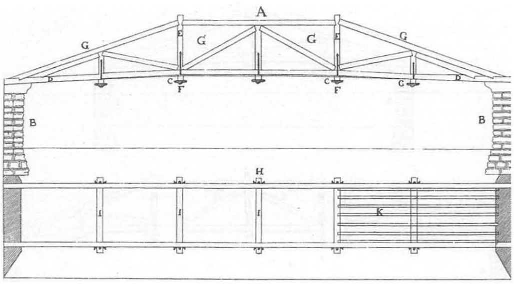

Figure 10
The Cismon river bridge. Palladio [1738] 1965

with the wedges at the top of the transversal beams, as a device for a softer union of the road with the course on the bridge, obtained keeping lower the profile of the course in comparison with that of the structure:[10] a disposition meant to improve the *commoditas* of the whole work, a quality clearly mentioned by the Author, also one of the three fundamental requirements (*firmitudo* and *venustas* are the others) indicated by Vitruvius.

The other fundamental advance is the connector, a true Palladio's invention in the modern meaning of the term, by him called «arpice» or «arpese», of which a detailed drawing is given here, Figure 11–14, a cramp, in a way a bolt, used as a device to connect the rulers convergent to the principal nodes of the structure in all his bridges.

The importance of this invention is that it allows the prefabrication of the work by means of the easy, therefore also quick and cost-saving, assembling of the members constituting the bridge.[11] It must be stressed that the same building process,[12] Figure 15, exposed for the Cismon bridge similarly to Caesar's bridge, is highly simplified by the use of the *arpesi*: in fact these are analogous to the *fibulae*. The invention of the arpesi has probably been suggested, as key of the whole mechanism, by the reflections about the Caesar's connectors.

Palladio gives an accurate description of the arpesi, also shown, at least partially, in his drawings, and many Authors have tried to interpret the description, mainly with drawings.[13]

In a literal interpretation, from the text, of the shape of the arpesi and with a close exam of the drawings of the Treatise, they are flat (*diritti, e piani*) and perforated (*forati)* where they are to be connected, by means of nails (*inchiodati*), to the uprights (*the colonnelli,* «small columns»); they are thick (*grossi*) where they pass trough the hole made at the ends of the transversal beams (fatti passare per un bucco fatto a questo effetto nelle teste delle dette travi . . . che fanno la larghezza del ponte). Because the hole in the transversal beams, 27 cm thick, can only have cylindrical shape (except in complicate and expensive workings to make them with a square or rectangular section, which are not usual, because expensive, in building carpentry), this part of the arpesi can only be of the same shape and of the same calibre of the holes in order to fit them in the best way. The arpesi were probably obtained by segments of round rods heating and hammering one side to make it flat, then operating the perforations at the top and at the bottom. The arpesi are solicited mainly to tensile tension in the longitudinal direction, also at shearing tension at the section close to the connection between the side beams and the transversal ones.

The arpesi are locked (*serrati*) at the lower end by means of small iron bars (*stanghette*) that we can imagine in number of two, wedge-shaped, each one

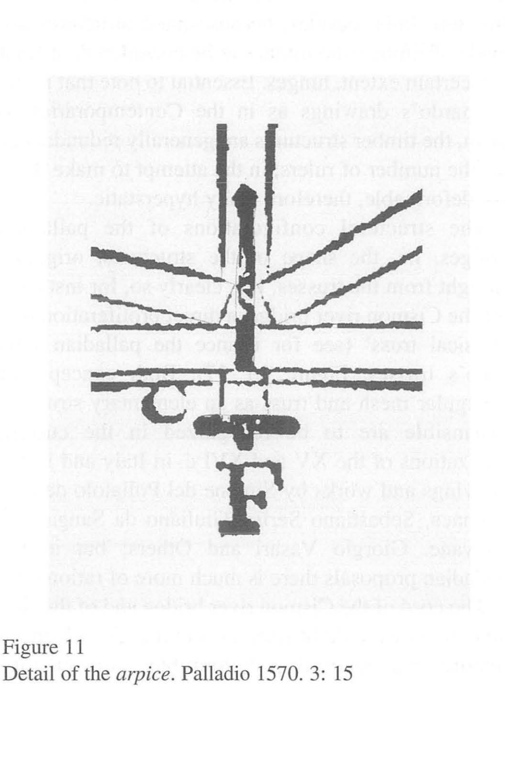

Figure 11
Detail of the *arpice*. Palladio 1570. 3: 15

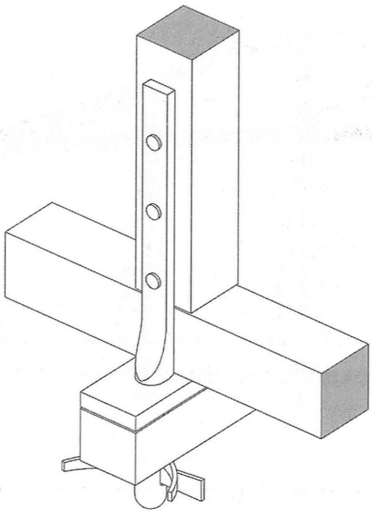

Figure 12
Palladio's *arpice* interpreted by Gennaro Tampone; perspective drawing made by Pietro Copani

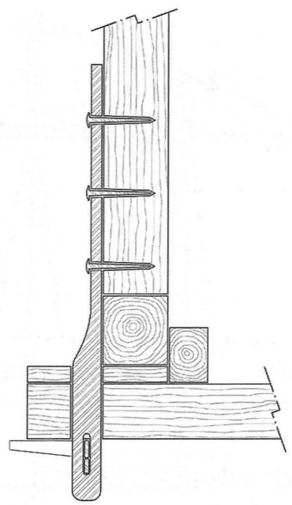

Figure 14
Palladio's *arpice* interpreted by Gennaro Tampone; section drawing made by Pietro Copani

being bent at the narrower end, which meets the notations of both the drawings given in the Treatise, the side view and the plant. Palladio shares with Giorgio Vasari, a contemporary of his, the merit of having given special attention to the iron connectors in the timber structures and designed precocious, effective devices[14] which would not be paralleled by anything similar for at least the two following centuries.

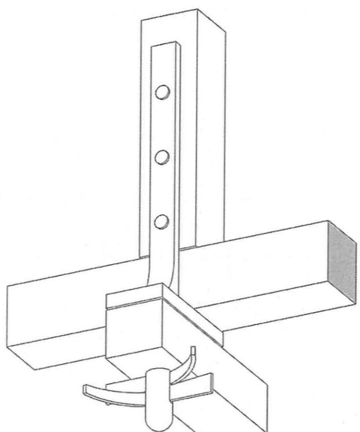

Figure 13
Palladio's *arpice* interpreted by Gennaro Tampone; perspective drawing made by Pietro Copani

Modularity is achieved by the standardized dimensions of the transversal beams, pierced at both extremities for the insertion of the *arpese* and therefore acting like a template, and by the side beams. It is worth noting that the side beams are kept in the assigned position by the arpesi and by the lateral «travicelli», i.e. the secondary beams, the firsts preventing horizontal sliding movements outwards, the others inwards.

For the connection of the six segments constituting the side beams or the bottom chord of each of the two girders in the Cismon bridge,[15] (with a different interpretation Mainstone maintains that «its bottom chord was shown as continuous throughout the span, though it is doubtful whether single timbers of the required length could have been found») which are not drawn in details in the Treatise, suggestions (see drawings) can come from the central connections in the chords of the trusses of some palladian buildings, by instance Villa Badoer in Fratta Polesine. The

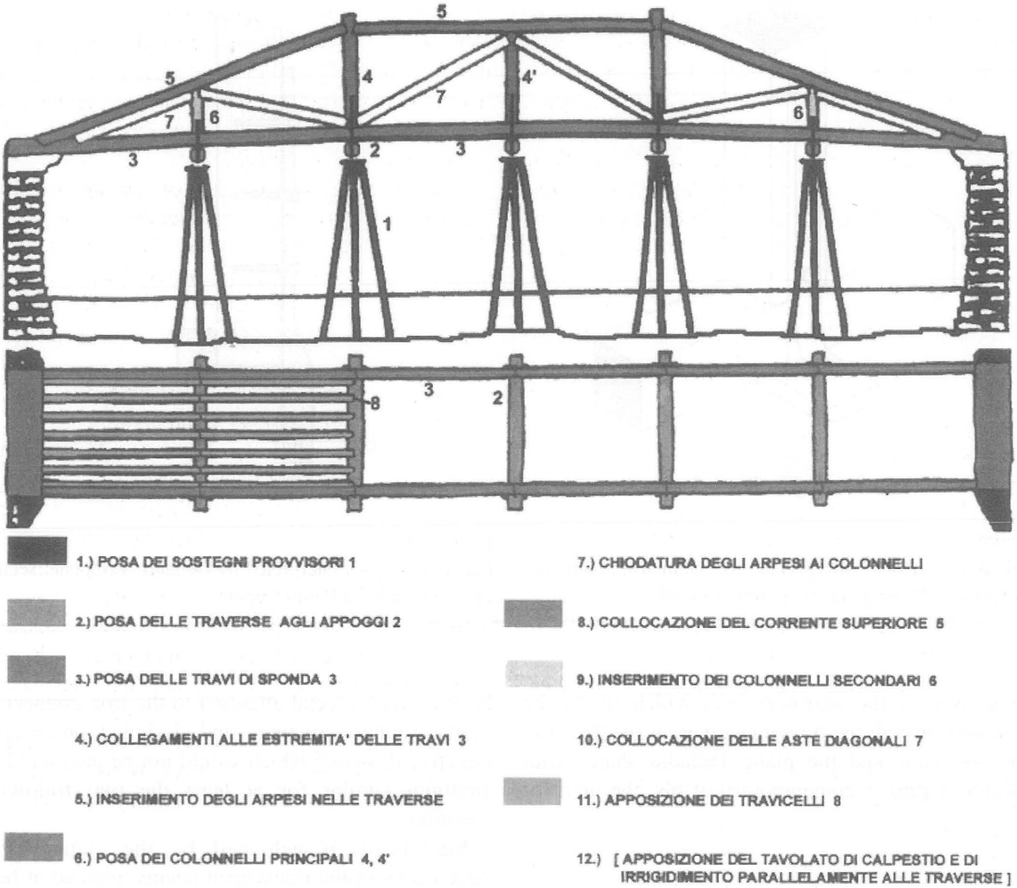

Figure 15
Building process of the Cismon river bridge

connections of the members of the timber tie (*catena dè castagni*) designed (according to a traditional technology) in the first twenty years of the XIV century by Filippo Brunelleschi for the dome of the Santa Maria del Fiore in Florence (Tampone, 1996), still *in situ*, can also provide useful suggestions.

Russo Ermolli, assuming the hypothesis that the bridge is conceived as constituted by two lattice girders on two hinges, one of them with possibility of horizontal sliding, calculated[16] in somewhat less than 50.000 kg the stress in the segments (about 50 kg per square cm), an enormous tension for this kind of joints: Tampone had already expressed in his latest contribution on the matter[17] (where also other inconsistencies are evidenced) his doubts about the efficacy of tended joints to face this stress, especially in the long term.

Therefore the authors of the present paper suggest here that a different possible hypothesis, on which research has begun, should be taken into account, namely that both hinges cannot move in the horizontal direction, for instance in force of the shape of the piers. The side beams would be in this case compressed, the joints of the side beams would be very simple, the extremities of the segments would be just cut almost perpendicularly to the longitudinal

axe, and faced. The arpese and the *travicelli* would keep them in the designed position. Palladio's words: «onde le parti una per l'altra si sostentano, e tale viene ad essere la lor natura, che quanto maggior carico è sopra il ponte, tanto più si stringono insieme, e fanno maggior la fermezza del ponte (Caesar: Tanta erat operis firmitudo, atque ea rerum natura, ut quo maior vis aquae se incitavisse, hoc arctius illigata tenerentur)» would acquire a more specific and fitting meaning.

Fundamental is the innovation of the dimensioning of the timbers, of which Palladio does not give the criteria but the values only (Cismon bridge): $^{3}/_{4}$ of foot of Vicenza the breadth (27 cm), 1 foot (36 cm) the height.

The proportion between base and height of the beams, 1,333, is[18] consciously, by intuition, chosen very close to that of the maximum strength, i.e. 1,4142 for a bent timber member obtained by a shaft.

All the members of the two lateral girders are thinner and narrower than any member of Caesar's work: the remarkable result is obtained, no doubt, because the Architect's configuration is that of a structure conceived as a unit with an excellent distribution of the tensions.

The supplementary ruler at the ends of the rafters, where the tensions are higher, is also very appropriate; the same device is applied in the structural design of the most advanced architects of the time, for instance Giorgio Vasari at the ceiling of the Salone dei Cinquecento in Palazzo Vecchio, Florence (1563–1565), Giuliano da Sangallo il Giovane (about the same years, drawings in the Uffizi's Drawings Cabinet) and so on.

The dimensions of the transversal beams having the same dimensions of the other members, with a span of 4,40 m and with a bay of almost 6, and of the *travicelli* which cover a span of about 6[19], are still problematic. Furthermore, it is impossible to explain the stability of the bridge without transversal bracings at least at the upper level of the girders, omitted in the Treatise.[20]

The bridge designed in the «prima inventione», Figure 4, is of outstanding importance because an other element of bridge-planning is introduced: the special building process. Here the invention is the progressive launching of parts of the one-bay bridge, which are temporarily supported, at both sides, by the parts already built, that means without piers nor centrings. Due to the difficulties of imagining for such a bridge the position and the role of each member, not only in the final destination, but also during the transfer, we must take for granted that Palladio prepared solid models of this invention and, probably, also of the others.

A major problem is the lack of bracings in all the bridges. It has been supposed that they were present, the lack of indication in the Treatise being an omission. It ought to be remembered, however, that the awareness of the necessity of such members was completely reached only at the end of the XIX century.

The use of the arpesi and the prefabrication, in general, give raise to another kind of problem, namely the deformability of the work, which is higher for a structure with a large number of joints.

Palladio's technical drawings in orthogonal projections of his timber bridges were designed for the Treatise, which means some twenty years after the realization of the Cismon bridge. But we must assume for sure that he also used models, i.e. maquettes, as it was customary and as is documented for his very famous bridge of Bassano.[21] Models were very useful because they could allow the understanding by everyone even if not a technician, to ease the study of structural details such as the joints, for the estimate of the whole work and the forecasting of the time necessary to completion.

The fortune of Palladio's timber bridges

Palladio's Treatise was disseminated everywhere in the centuries following its first edition and the Palladian timber bridges became very famous, in part because of the graciousness of the drawings. A more critical and technical approach to these bridges was adopted beginning in the XVIII c., for instance in the treatises on the bridges written by Gautier,[22] by the Encyclopaedists, and later by Gauthey,[23] where attempts to interpret Palladio's inventions are to be found. Rondelet's fundamental work, edited at the beginning of the XIX c. and disseminated in all Europe, marks an important moment in the scientific interpretation of the objects of our study. In England, thanks to two important editions of Palladio's work in the XVII c., the Promoters of the Palladian Revival, Palladian projects were highly appreciated and the

bridges amongst these: reproductions of the bridges were built, as footbridges and ornamental elements called «paladian», in the gardens and in the parks of the estates of the peerage.[24]

NOTES

1. The following chapters of Book III (chapters 11–15) are dedicated to stone bridges. Palladio 1570. 3: 21–30.
2. Palladio 1570. 3: 15–20.
   For the Cismon and the identification of the remains of the piers, see: Funis 2000. 15–18.
3. Palladio 1570. 2: 71.
4. Mainstone 1975.
5. Funis 2000; Tampone 2000.
6. Leonardo da Vinci 1901; Caesar C. J. 1514.
7. On this matter see, amongst the others, Funis, with systematic references. Funis 2000.
8. Tampone 2000; see also Mainstone, 2001, cit.
9. Leonardo da Vinci. 1987.
10. Funis 2000. 10–11.
11. Funis 2000; Tampone 2000.
12. Tampone 2000.
13. See, for instance, Laner 1997; Funis 2000; Copani Funis 1999; Tampone 2000.
14. Tampone 2000.
15. Mainstone 1975.
16. Russo Ermolli 1996.
17. Tampone 2000.
18. Funis 2000.
19. Tampone 2000.
20. See Funis 2000; Tampone 2000; Russo Ermolli 1996.
21. Azzi Visentini 1980. 25.
22. Gautier 1716.
23. Gauthey 1843.
24. Ruddock 1979.

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Structural invention and production process in the Pier Luigi Nervi's work

Gennaro Tampone
Nicola Ruggieri

Pier Luigi Nervi (1891–1979), a structural engineer, also called the «Constructor» or the «Architect», started his practice in the late years Twenties and continued till the early Seventies. This long, fruitful period includes the development of his structures and the studies and testings about the structural precasting. At the same time, he designs several buildings, from the first realizations as Stadium Berta in Florence (1929–1932) and the Hangar in Orvieto (1935), Figure 1, to the followings of '40s and '50' (Exposition Palace in Turin, the Small Sport Palace in Rome, the Pirelli Skyscraper in Milan), until the american projects (St. Mary's Cathedral, San Francisco, Cultural and Convention Centre of Norfolk, Virginia).

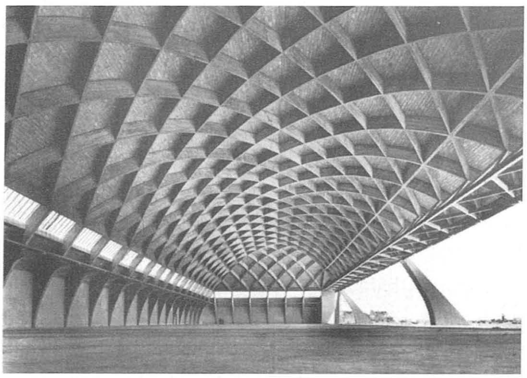

Figure 1
Hangar in Orvieto (1935)

The Nervi's approach to the building process is global.

This extraordinary achievement is reached by mastering all the factors which condition the building process, namely the experimentation of new structural configurations and of building process, the planning and the realization of specific constructions, the production of structural elements, the same building process meant as studies for a logical economical progression of the building activity and the planning of the provisional works, the aesthetic aspects, the economics of the construction.

The systematic survey of these factors, chosen as key to the interpretation of the Nervi's work, is the aim of the present paper.

The structural invention

The essential factor in the Nervi's practice is the constant attitude to conceive, experiment and realize innovative structural complexes.

In the important planning appointments or in occasion of calls for bids for large architectural buildings, especially where the presence of large vaulted halls is requested, Nervi does not plan his construction in the traditional way: on the contrary, the whole building is conceived from the foundation, also

in the vertical supports, even in anyone of the structural elements, as a rational composition of parts principal and secondary of the covering vault or floor. In the case of vaults, the research is carried out following the method of prefabrication of thin, light, strong elements, flat or grooved, which are placed in the final position and later connected by ribs of reinforced concrete cast in the empty spaces left on purpose between the same elements, this way producing a network of members which are oriented in two main directions and kept in their position by the prefabricated elements, a kind of warp of knitted tissue. Nervi shows to follow the great, noble constructional tradition in the research and realization of large-span, thin, light vaults as it has been manifested by the western architecture since the ancient roman time and continued in Europe and in the Near East, namely in Iran; to a very large extent, in fact, the research on vault planning is the most peculiar feature of the architecture of these constructional civilizations.

The researches on structural types are supported by those on building materials and especially on the reinforced concrete and on the *ferro-cemento* etc.

The first idea of the *fer-ciment* is due to Lambot and Monier in the XIX c.; Monier in 1855 got a patent for the construction of boats where the product is used in place of the wood, in 1867 an other patent for *caisse-bassins mobiles* to be used in gardening. Wayss and Koenen in Germany modified the original idea using boxing and a simplified reinforcement and opened the way to the modern reinforced concrete. The Cottancin system, 1886, using boxing and a very dense net of iron wires, was later used in a systematic way by Anatole de Baudot for his architectures like, for instance, the Church of St. Jean in Montmartre.

Amongst the many Nervi's inventions and realizations, one of the most interesting is the so called «*strutture cementizie ondulate*», Figure 2, (patent of industrial invention 1948), i.e. the corrugated vaults.

The invention consists in the use of thin prefabricated elements long from 2 to 3 m of *ferro-cemento*, with the cross section shaped as a semi-wave, Figure 3, (in some versions with square corners); steel bars come out of the body of the elements in order to realize an efficient transversal connection between the single pieces.

To avoid instability of the long, thin elements during the transfer and when in situ, triangular,

Figure 2
Main Hall of the Exposition Palace in Turin (1950). Prefabricated beam

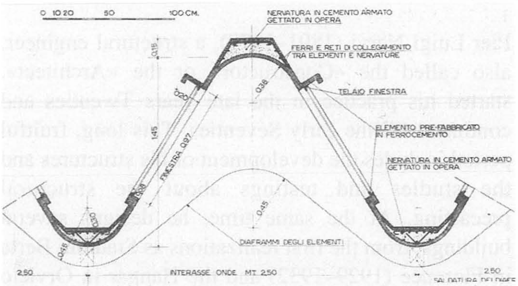

Figure 3
Main Hall of the Exposition Palace, Turin (1950). Drawing of the pre-fabricated cover element

therefore indeformable, meshes of braces prefabricated in the same way, are added to the elements; in some versions these are completed with smart undulated transversal diaphragms which have the same function of the bracing. The triangular bracings and the diaphragms are used as stiffenings during the transfer in the site of the yard, when are in situ become part of horizontal rings —like parallels of the globe— which are connected with the radial elements —half-meridians— of the waves.

A parallel can be started with the early Brunelleschi's idea and realization of the dome of Santa Maria del Fiore in Florence, which was provided with one stone collar tie at the base and with a timber one in the middle and with the

Michelangelo's dome in St. Peter in Rome which was provided in construction with five iron «cerchioni» (some more were added later by Vanvitelli, on Poleni's instigation, as consolidation device).

By means of temporary supports, the elements are put close to the adjacent ones in order to form a succession of waves to define a covering having the chosen shape; they are later connected (see the chapter on Prefabrication) by ribs in reinforced concrete, put at the bottom and at the top of the waves along the radial direction, cast on the spot, Figure 4.

An important role is played in the planning of the Nervi's structures by experimentation also because, as the Author says, it was impossible for the time to calculate the kind of structural systems he was conceiving.

The planning and the realization of specific constructions

This invention of shapes and procedures was extremely fruitful of important realizations:

Swimming Pool of the Accademia Navale in Livorno, 1947–49, the Exposition Palace «B», Torino, 1947–49, the Canopy for Milano Fiera, 1953, Project for the Sport Palace, Wien 1953, Sport palace, Rome, 1958–59, Figure 9, Viaduct Corso Francia, Rome, 1958–59, Papal Hall, Città del Vaticano, 1966–71.

Later Nervi perfectioned the structural conception and got the patent «*Perfezionamento nella costruzione di solette, lastre e d altre strutture cementizie armate*», 455750, 1950, with the realization of the Tobacco factory, Bologna, 1949, Figure 5.

An other very interesting patent, 455678, 1950, is concerned about the disposition of the structural ribs along the isostatic lines of a covering or a vault, Figure 6.

Realizations are the Wool Factory Gatti, Rome, 1951–53, Entrance Canopy at the UNESCO Palace, Paris, 1953–58, Sport Palace, Rome, 1958–59, Labour Palace, Turin, 1959–60, Entrance to the Papal Hall, Città del Vaticano, 1966–71, Figure 7.

With the patent on «*Procedimento di costruzione per la realizzazione di superfici resistenti piane o curve costituite da reticolati di nervature in cemento armato, completate o meno da solette di collegamento tra le nervature*», n° 465636, 1951, Nervi realized the following works: the semi-spherical dome of Exposition Palace «B», Turin,

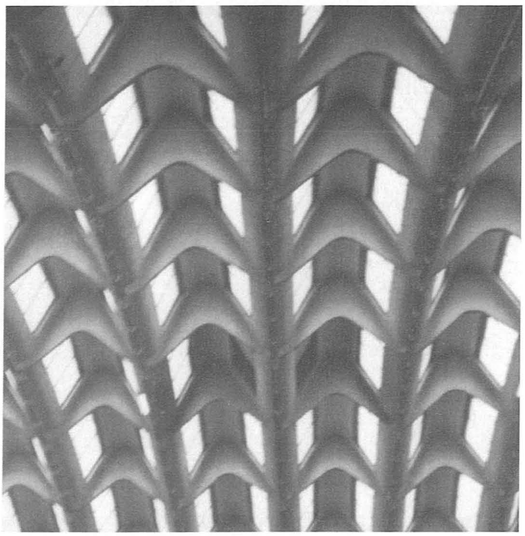

Figure 4
Main Hall of the Exposition Palace in Turin (1950). A view of the prefabricated cover beam

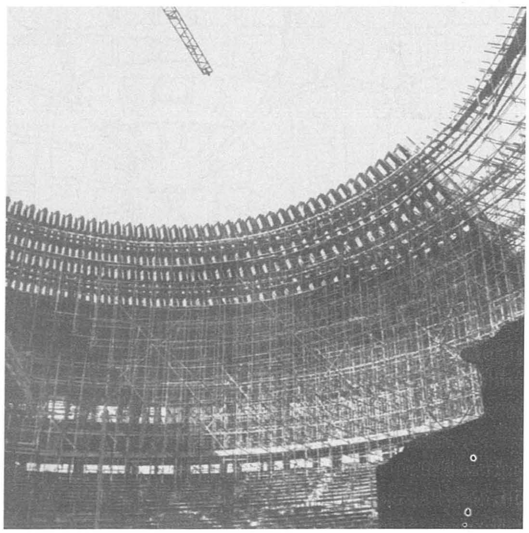

Figure 5
Sport Palace in Rome (1959). Assembly of the pre-fabricated elements

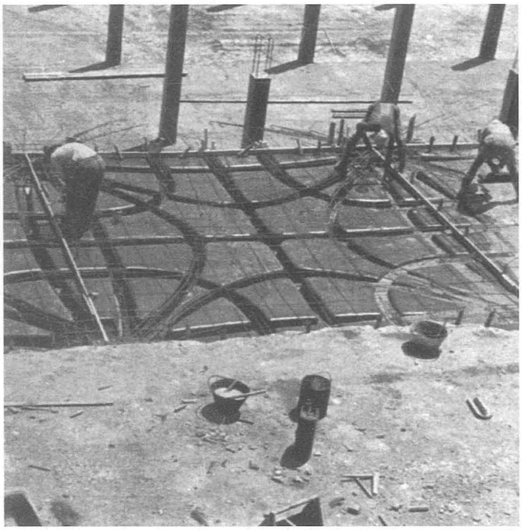

Figure 6
Tobacco Factory, Bologna (1949). *Ferro cemento* boxing

Figure 8
Papal Auditorium in Rome (1971). A view of the entrance floor.

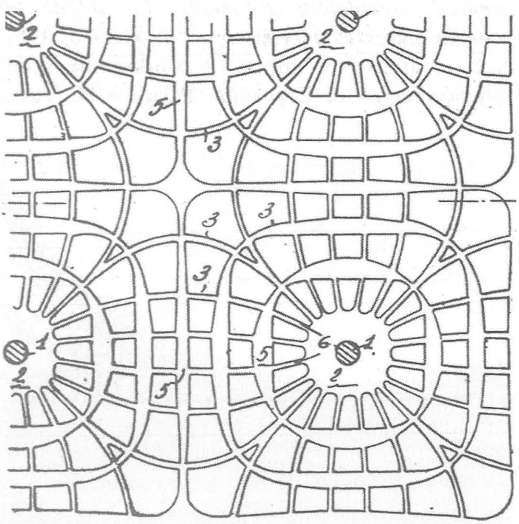

Figure 7
Floor with the ribs positioned along the isostatic lines of the moments

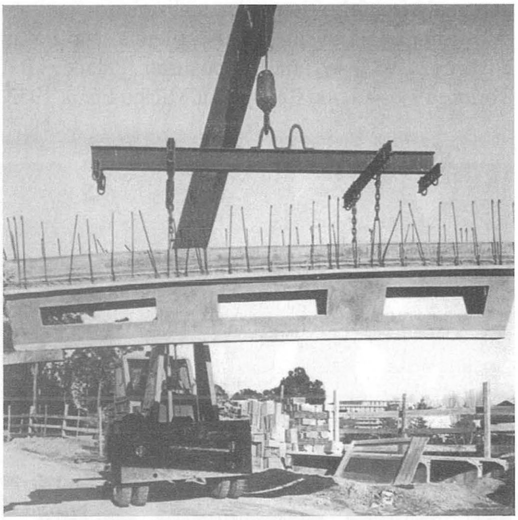

Figure 9
Small Sport Palace, Rome (1959). Cover pre-fabricated element

1947–49, the vault and covering of the entrance gallery to the Exposition Palace «C», Turin, 1949–50, covering of the Restaurant Kursaal, Lido di Roma, 1950, Storage for the salt, Tortona, 1950–51, covering of the Fests Hall of the Thermae, Chianciano, 1952, Small Sport Palace, Roma 1956–57, Figure 8, project for the Benedictine Cathedral, New Norcia, Australia, 1958, vault of the

Field House of the Dartmouth College, Hanover, USA, 1960–61, Bus Station, New York, 1960–62, Building Australia Square, Sidney, 1961–67, St. Mary's Cathedral, San Francisco, 1966–71, Culture and Sport Centre, Norfolk, USA,1966–68.

These researches on materials and on methods of vault planning are announced in the two hangars Nervi planned in Orvieto in 1935, organized as an only coved vault starting with its supports from the very ground and developing as a network of ribs diagonally moving from one to the other of the longest sides of the building. The entire building, the ribs and the other portions, allow to get over a span of 50 m.

Another roof system, tested by Nervi, is the mushroom floor, used in the Labour Palace in Turin, where the reinforced concrete pillars show a variable section, and are covered by metallic elements placed along the radius, Figure 10, Figure 11.

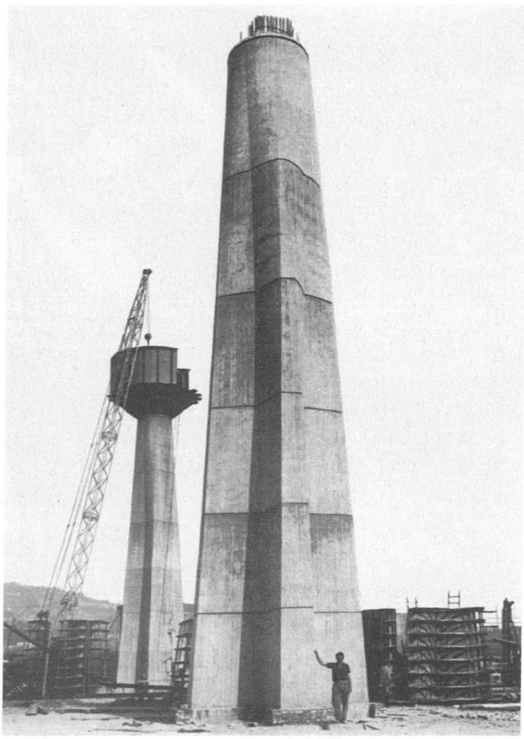

Figure 10
Labour Palace in Turin, (1960). Execution of the pillars with a variable section

Figure 11
Labour Palace in Turin, (1960). A view of the pillar with a variable section

The very large number of realizations of vaulted buildings proves the fulfilment of this task.

THE PRODUCTION OF STRUCTURAL ELEMENTS, THE PREFABRICATION

«La prefabbricazione apre ai progettisti i più ampi e promettenti campi della vera e grande architettura» profetically said Pier Luigi Nervi in 1955. The *ferro-cemento* in the version for which Nervi got a patent in 1943, is constituted by several layers of iron net (thickness inferior to the millimetre and meshes of about one centimetre), connected by thin iron wires; this skeleton is later covered by concrete of plastic consistence, with modest mechanical properties, made with high quality, high percentage cement melt with water and sand. The composite *ferro-cemento*

has very peculiar properties such as: perfect structural isotropy, due to the homogenous distribution of the reinforcement; an excellent behaviour both to tension and compression; high elongability and, at the same time, high superficial tension, properties which prevent it from cracking, «*inrompibile*» as Nervi defined it with an Italian neologism. The boxing, made of wood or metal or chalk, to be used an indefinite number of times, is laying on the soil during the positioning of the reinforcement and the cast of the concrete; bottom and side surfaces can be smooth or dressed according to the refinement quality and level requested for the final product. The prefabrication allows to realize elements with a curved surface and the presence of material only where really needed for the structural function, something which is rather difficult and anyhow very expensive with the traditional reinforced concrete. The possibility of connecting all the elements prefabricated in the said way by means of a network allows the monolithicity of the work.

In the case of the grooved vaults, a steel reinforcement of longitudinal bars (high resistance steel if a pre-tension is planned) is placed, from the extrados, at the bottom of the wave and at the crest; concrete is poured on both reinforcement to form radial ribs from the top of the vault to the springings. The resistant masses of steel bars, being placed at the maximum distance from the neutral axe, as Nervi says in the patent request, exploit the maximum efficacy. It is clear therefore that the waves have the function to keep the steel reinforcement, in a way they act as distancers even if they co-operate to the bearing function; in fact they can have voids for windows at one or at both sides, as Nervi says, besides they realize the closing of the building and do not need further protection against weather because they are water-proof and «*infessurabile*» an other nervian neologism like «*inrompibile*» .

Prefabrication, coupled with seriality, is in fact present in almost everyone of the Nervi's work. Already in the early realization of the Hangars in Orbetello, Figure 12, Tuscany, the ribs of the coverings are prefabricated on the ground of the yard.

The boxing was put lying on the soil. The maximum care was put in the design and execution of the joints, Figure 13, Figure 14.

The same building process was meant also as a series of studies for a logical economical progression

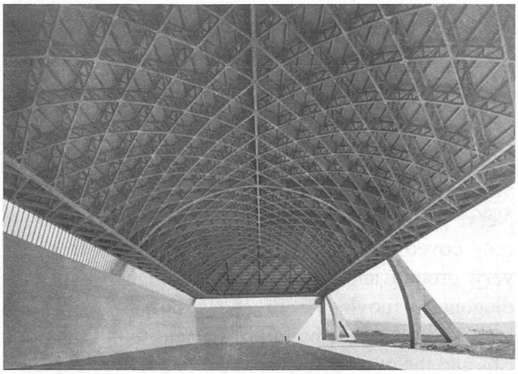

Figure 12
Hangar in Orbetello (1940)

Figure 13
Hangar in Orbetello (1940). Pre-fabrication yard

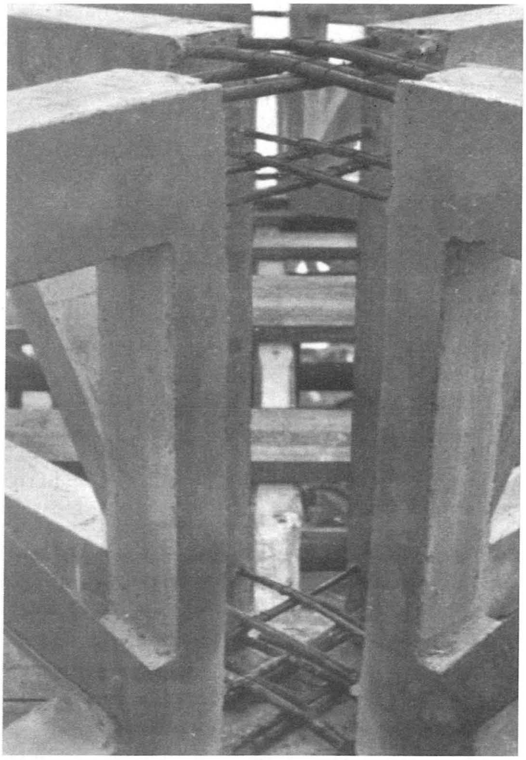

Figure 14
Hangar in Orbetello (1940). A view of the pre-fabricated element node

of the building activity and the planning of the provisional work.

The same operational progression of the building activity is quicker because several elements can be done contemporaneously, for instance whilst foundations are prepared the pre-fabricated elements can be cast.

The aesthetic aspects

To discover the essence of the Nervi's aesthetical theories and at the same time to find a key to the interpretation of his works we need to recall some of his most important statements.

«L'indipendenza di spirito . . . è una condizione assolutamente indispensabile per quanto riguarda il lato estetico.»

«Il carattere di una costruzione non dipende dalla sagoma delle modanature, dalla dimensione delle finestre, o da qualche particolare carattere decorativo, ma fondamentalmente dai rapporti di volumi, di forme, dalle caratteristiche delle strutture portanti, da quel complesso, insomma, di elementi che riguardano non la rifinitura ma lo scheletro e l'organismo strutturale dell'edificio.»

The pilasters of the large halls, for instance, like those of the Papal Hall in Vatican, are shaped by a dynamic conception of the supports: they are very few, dynamically inclined to meet the covering, establishing in a natural way the connection with the soil and starting the very vault, in some cases continued in the covering as arched ribs; they are faceted to reflect the light in different tonalities as sculptures, oriented at the top in the opposite direction of that at the base to meet different orientation of the internal tensions therefore showing the stresses they are facing.

In the coverings, an important aesthetic factor capable to produce patterns of extreme interest, is the seriality of the elements and the alternation of voids and nervures, as it was to be assumed as the dominant motive in the Calatrava's architectural expressions. Precious interesting effects of vibration are produced by the undulation of the elements and the wise use of openings in the lateral sides, the less stressed.

The large halls reach an impressive monumentality by means of the absence of intermediate supports and the same very wide span of the structure.

The most interesting effect is given by the complete integration between architecture, function and structure. Architecture and Structure as nerves and sculpture are to be seen in many of the Nervi's works as the many Halls he planned and in this attitude the Constructor follows or starts, a trend which was also followed by Mallart, Le Corbusier, Marcel Breuer, Morandi etc. The structure, in a period when it is, at least in Italy, generally hided by marble or more traditional materials, in the constructor's conception, on the contrary, is exalted and proudly shown.

Fortunately, the Nervi's ideas and conception in architecture with experimentation, new materials, new structural conceptions, prefabrication etc. therefore large span halls, daring overhangs, expressive members and structures, met the requirements of the new Italian industrial leading

class which thought to be well represented by architectures which were a challenge to the traditional materials and execution techniques as well to the laws of the static; this explains, at least partially, the Builder's fortune.

THE ECONOMICS OF THE CONSTRUCTION

Low cost of the labour in comparison with that of the building materials therefore the optimization of the process is one of the more important targets in the period Nervi was operating.

Many economies came from self-construction because Nervi also acted as Contractor, i.e. easiness, speed and precision when assembling: every piece's end is inserted in the apposite hollows of the other or there is a final cast of reinforced concrete to connect all the elements. Besides: minor incidence of the transportation, stocking in the same yard of the production, the possibility of reducing the execution time by means of contemporary working of the different parts of the construction, finish of the outside surfaces of the elements by means of suitable boxing, preparation of the concrete suitable also for insulation, superficial waterproofing, eventually clear and programmable budget were the main economic factors of success, especially in the offerings presented in the calls for bids.

CONCLUSIONS

Nervi introduces an original conception of the load bearing structure which goes far beyond the traditional articulation, in a building, of the different constituting elements such as structural members and curtain walls or internal partitions, i.e. bearing elements and supported parts: he reaches, by means of the building process, a global organization where every element plays a role in supplying, even in different proportions and ways, a contribution to resistance, equilibrium, stiffness, impediment to deformation, in order to ensure the general efficiency and stability of the whole system. In a period in which the load bearing structure is essentially meant as a well defined resistant skeleton separate from the other parts and, especially in Italy, the reinforced concrete is the material deputed to realize it —also steel but only to a minor extent—, the Nervi's structural conception is closer to the attitude of the classic period, when the architect was the protagonist of every building phase or activity, but of course on completely new bases; these are the possibility of using a material resistant to both tension and compression other than wood, the possibility of casting it in the desired shape and the monolithic quality i.e. the effective connection of all the members.

This turns into a general expressivity of the structure where every member that is co-operating to stability is exactly planned in shape and dimensions in accordance with the distribution of the internal tensions and shows clearly the role it is playing. Strong suggestions came to Nervi by the Futurism, and these are to be recognized in the daring cantilever canopy of the UNESCO Palace in Paris, the Maratona

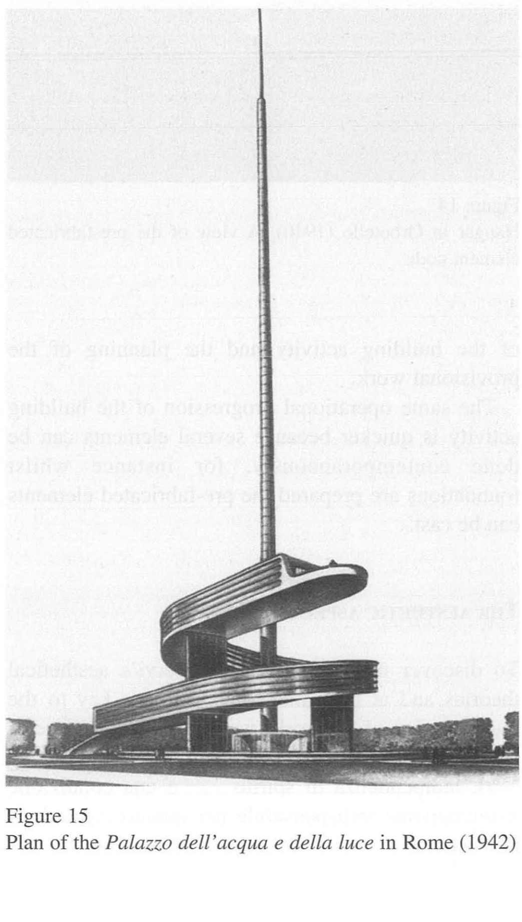

Figure 15
Plan of the *Palazzo dell'acqua e della luce* in Rome (1942)

Tower and the helicoidally shaped staircases of the Gymnasium in Florence, in the graphic rendering of the project for the Palace of the Light and the Water in Rome, Figure 15.

The period of «*autarchia*», i.e. the embargo, very mild in reality (Italy was not, in fact, short of iron and was a middle producer of cement), acted by the European Nations with the consequent shortage of some important building materials, the large use Nervi did of the *ferro-cemento* was in opposition to the trend. The Nervi's ideal and practical experience was concluded with his person, the architecture took later other ways.

An important thought when speaking about the Nervi's practice is the fact that he acted as Planner, Clerk of works, Contractor and Producer, position which gave him the rare possibility of complete control of the building process and of the costs and allowed to experiment structural systems as well as large scale pre-fabrication.

Nervi was in contact with some of the leader planners of his time; Piccinato, Libera, Vaccaro e Ridolfi came to his house in Rome, Bardi, Danusso, De Finetti, Rogers were meeting him in Milan but in architecture he took always an isolated and original position. Nevertheless he is to be considered one of the most important Masters of the Rationalism and Functionalism.

A very interesting contamination and strong analogies for the use of grooved vaults are to be noticed between the reinforced concrete and the use of timber for structural purposes like the pavilions realized in wooden boards by the famous Firm of prefabricated structures Legnami Pasotti, Brescia, and planned by Adalberto Libera and Mario De Renzi, especially the Winter Garden of the National Fascist Party (Libera, De Renzi and Guerrini, 1938).

Also very interesting is the fact that in the timber structures too of the period the pre-fabrication, at an handicraft level, was also pursued and this happened in the same way adopted by Nervi, i.e. the system of designing on the soil the shape of the arches which were to be realized in wooden boards assembled and nailed together. This can be explained by the fact that the cost of labour was very low in comparison with that of the materials.

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The Early use of Reinforced Concrete in India

Stuart Tappin

The question of what were the early reinforced concrete buildings in India generally evokes mention of the city of Chandigarh and the involvement of Le Corbusier. But that was built from the mid–1950's, are there no reinforced concrete buildings from the first half of the 20th century? If there were, where and how was reinforced concrete used? Who were the designers? What was done to suit Indian contexts such as climate, materials and skills?

Apart from the buildings designed by Lutyens and Baker for New Delhi there has been little interest in any aspect of India's buildings from the first half of the 20th century. One reason is that the buildings of this period began to take on a more international appearance, replacing the exoticism of the Indo-Saracenic buildings from the late–19th century that was, and remains, so appealing to writers on India's architectural history. Another reason is that many of the buildings were designed by architects who are almost unknown outside of India and so have not attracted the attention of western architectural historians.

What has been written on the built environment has generally concentrated on the architect and stylistic issues. For works on Indian buildings from the first half of the 20th century the writer will mention the architect if he (there are no references to female architects) was sufficiently important and will focus on whether a particular building fits into a particular Western-generated category such as Art Deco or Modern Movement. Apart from journals and publications written at the time there are no works on the engineers and builders, or details of the structure of the buildings.

There are contemporary and modern references to concrete buildings or the use of pre-cast concrete that do not fit into the chronology for the uses of these materials. By looking at the buildings in India in the broader context of the development of reinforced concrete elsewhere in the world it is possible to see if these references are correct. We can also begin to understand why different structural solutions were chosen for similar building types and have an indication of what we might expect the form and condition of the structure to be for buildings of a particular date.

This study ends in 1947 at the end British rule in India and close to the end of the «pause» in building industry caused by World War II. This was also a period of transition for building in India. Although Anglo-Indian architects continued to practice after the war they were eclipsed initially by Le Corbusier and Louis Khan —high-profile names brought in to help promote a modern India— and then by Indian architects such as Charles Correa, Balkrishna Doshi and Raj Rewal.

Buildings from the first half of the 20th century form a large and important part of India's built environment and it is important for economic, environmental and conservation reasons that their

form, condition and qualities are understood. There is a small but growing awareness in India, as elsewhere in the world, that the conservation of good quality buildings, including those from our recent past, is important for the well being and prosperity of its cities and its citizens. Mumbai has taken the lead with planning legislation in 1991 to protect individual buildings and areas within the centre the city. There are however, other important buildings that deserve to be recognised for the positive contribution they bring to an area or neighbourhood. As we shall see, a number of these buildings are also important for their place in the development of reinforced concrete construction in India.

A note on place names; Bombay is now called Mumbai, Madras is Chennai and Calcutta now Kolkata. The original name has been where a historic reference is given, e.g. «materials testing in the 1920's was carried out at colleges in Madras, Roorkee and Sibpur».

What is Reinforced Concrete?

In the second half of the 19th century a number of ways of combining iron and concrete, and later steel and concrete, to produce more efficient, and hence, cheaper structures were developed. The origin of reinforced concrete in England is generally accepted as William Wilkinson's patent in 1854 (Hurst, 1996, 290). His system was not widely adopted however and most of the early developments and successful patents came from Germany and France. The method of reinforced concrete flooring patented by Francois Hennebique in 1892 was the most widely used, such that by 1909 nearly 20,000 structures had been designed using the Hennebique system and the company had 62 offices including four in Asia (Newby 1996, 267 & Bussell 1996, 297).

The patented system meant that the contractor paid for a structural design, licence for the materials and instructions on how to build to a particular system. For the early engineers and contractors in India without the education and experience of using reinforced concrete this method of procuring a design and then constructing on site with unskilled labour had obvious advantages. India followed the UK in adopting a standardised approach to the design and construction of reinforced concrete following the introduction of regulations, codes and standards from 1915 (Bussell 1996, 319).

Reinforced concrete was used in the 19th century, mainly for foundation work. As early as 1869 hoop-iron was put in the concrete foundations of the High Court in Calcutta (Anon 1, 1869, 857). In general, most references to pre–20th century concrete buildings in India need to be treated with care since they will almost certainly be unreinforced concrete. One example is «Concrete-Building at Simla, India» published in 1886. This refers to the construction of two large buildings, the Secretariat and the Army Headquarters. Both are iron-frame structures using mass concrete for the foundations, the walls, and the floors where it was cast onto curved corrugated iron spanning between beams so that the concrete worked as a series of arches. The concrete used was made manually on site from lime burnt in local kilns and crushed brick (Smith 1885, 391).

Materials

Two of the basic components of reinforced concrete, Portland cement and steel, are formed by industrial processes that require a large initial investment in manufacturing plant together with a trained workforce. The early reinforced concrete buildings in India used imported cement and reinforcement, with only the aggregate being obtained from within India.

The Indian Cement Company was the first to start producing cement, in 1914 at a factory in Porbander on the Gujarat coast. This was marketed as «Ganapati' Best Portland Cement» (Kotasthane, 1919, 3). In 1914 India manufactured 945 tons of cement and imported 150,530 tons and the demand was such that London agents were buying German cement to re-export to India (Anon 2, 1911, 143). A second factory opened in 1915, in Katni in the Central Provinces —now Madhya Pradesh— that was able to produce up to 35,000 tons of cement per annum. Other factories developed around the country so that by 1929, although the total weight of cement used in India more than quadrupled since 1914 to 632,653 tons, the ten Indian companies were able to produce nearly 90% of the total (Anon 3, 1929).

The steel reinforcement was initially imported from the UK though agents in Bombay and Calcutta.[1]

Tata were the principle manufacturer of reinforcement in India from circa 1914.[2] Their quality was such that the Indian Public Works Department Handbook for 1931 notes that «reinforcement . . . should be best British or Tata's mild steel plain rounds or squares with an ultimate tensile strength of at least 60,000lbs/sq. inch». (Marryat 1931, 375).

The testing of materials to comply with the relevant Standards was initially at the Engineering Colleges at Roorkee, Madras and Sibpur (Stokes-Roberts 1910, 129). An example of the concrete quality comes from the construction of the road bridge over the river Nerbudda, built between 1929 and 1935. The compressive strength of the cubes ranged from 24–35 N/mm^2 (Dean 1936, 185), which compares favourably with a design compressive strength of 20 N/mm^2 in the 1933 revision of BS 12.

There is a reference to bamboo being used in place of steel for the reinforcement of piled foundations in the Far East in 1929, and for a small, undated, experimental structure in Nagpur with a 90mm deep flat roof slab reinforced with 12mm square solid bamboo splints (Bose 1950, 26). There is no evidence of the widespread use of bamboo.

Who were the designers?

The early reinforced concrete structures were designed by British military engineers, with Major Stokes-Roberts R. E. referred to as «instrumental in introducing the use of reinforced concrete and brickwork for Government purposes in India» (Marsh 1904, 522). The first structures were small-scale but this early knowledge meant that members of the Royal Engineers were also involved in designs for commercial clients such as the reinforced concrete flats for mill workers at Spring Mills, Bombay built in 1916 (Anon 4, 1917, 163).

The buildings constructed by India's regional governments had been designed and built by the Public Works Department (PWD) since the mid-nineteenth century. There is little reference to the PWD when it comes to buildings constructed in reinforced concrete and the early part of the twentieth century saw the formation of commercial architectural and engineering practices and building contractors. By 1929 there were 25 architectural and 36 engineering practices, and 76 contractors who advertised themselves as specialising in concrete including a number who offered themselves as both the engineer and contractor.

The geographical spread of these firms gives a picture of the use of reinforced concrete in India in the late 1920's. Bombay had 33 contactors able to build in reinforced concrete, Calcutta had 12 —reflecting the preference of steel-framed construction— and there was just one in Delhi where the tradition of building in load-bearing masonry continued. Concrete was used in smaller towns and cities, such as for the Bombay Life building in Udipi completed in 1936 where workmen had to be brought from Bombay to train the local workforce (Anon 5, 1937, 207 & 1939, 15).

The most successful engineer/contractor of the inter-war period was John Gammon (1887–1973), a British-educated civil engineer who before the First World War had worked for the PWD in Bombay and wrote «Reinforced Concrete Design Simplified».[3] After demobilisation he return to India in 1919 and rejoined the PWD where he designed the pre-cast concrete piled foundations and in-situ r.c. domes to The Gateway of India, designed by George Wittet.[4]

While working on The Gateway in 1922 he formed J. C. Gammon Ltd. One of their first projects was to design and construct 178 warehouses for The Bombay Port Trust in Sewri. These are daring structures that were influenced by developments in structural analysis and building technology in Europe. The buildings, which are now mostly derelict, are the first reinforced concrete shell roofs in India, using a 150mm thick curved roof supported on columns to provide over 76,000 square metres of open-plan storage (Anon 6, undated, 1).

Within the metropolitan areas of Bombay and Calcutta over half of the engineering practices were led by British engineers with the majority of the design and draughting work carried out by Indian engineers and draughtsmen educated at colleges in Madras, Roorkee, Howrah (Calcutta), Pune and Karachi.[5] The private companies tended to attract the best architects and engineers and so they were also called on to design buildings that would traditionally have been dealt with by the PWD. One of the largest projects in Bombay in the late 1920's was the building of Bombay Central Railway Station, designed by the architects Gregson, Batley & King (Mehrotra & Dwivedi, 2000, 110). It was built by The Ferro Concrete Construction Company and it is likely

that they also designed the reinforced concrete structure.

A number of the documented reinforced concrete buildings refer only to the architect. For these, and the majority of undocumented buildings from this period the structure was designed and detailed by the builder/contractor.

WHAT WERE THE DESIGN GUIDES?

For the pioneers of reinforced concrete in India the design was based on patents or empirical methods and load testing. In 1910 Major Stokes-Roberts wrote to suggest that reinforcement be added to mass concrete footings where the quality of the underlying ground is poor, but that «until trials have been made and data collected . . . it is impossible to say how much or how little steel should suffice» (Stokes-Roberts, 1910, 11).

As the understanding of the material increased the British Standards and Codes of Practice were adopted by the British administration in India. The cement could be imported or manufactured in India, but had «to comply in every respect with the latest British Standard specification for slow setting Portland cement» (Marryatt 1925, 377). This resulted in some curious requirements. For example the 1920 revision of the British Standard for cement, BS 12, required testing using sand provided by a contractor in Leighton Buzzard, with Indian cement manufacturers having to import the sand to achieve compliance (Davy 1921, 149).

Alongside the British Standards most offices were equipped with British textbooks that were augmented with Indian publications like Gammon's book referred to previously and «Reinforced Cement Concrete Construction» by Kotasthane published in 1919. The PWD Handbooks also provided advice on design, good working practices and standard details of Indian-style building elements (Davy 1921, 384).

There was an awareness among engineers of the problems caused by the high temperatures in India. In 1929 H. F. Davy produced a paper referring to a discussion as early as 1895 at the Society of Engineers in London on the accelerated setting time of cement in the tropics. Davy showed that the higher temperatures in India than the UK meant that the specification for Portland cement needed to be adapted in order to slow down the curing time (Davy 1921, 144). There is however no indication that changes to the specification were made during this period.

Another area where the British Standard was adopted without proper consideration for the Indian climate or the unskilled workforce was the amount of concrete cover. The guidance for cover to the reinforcement given by the PWD in 1925 (Marryatt 1925, 384) was:

- For columns: not less than 1_ inches (37mm) to the vertical bars.
- For beams: not less than 1 inch (25mm) to the longitudinal bars.
- For slabs: not less than _ inch (12mm) for any bar.
- For other members (such as lintels): not less than 1 inch (25mm) to any bar.

For columns and beams this meant that the secondary reinforcement, typically 6mm diameter link bars that wrap around the main bars, had a very limited amount of concrete cover. The use of aggregate up to 63mm wide was permitted (Marryatt 1925, 130), so if the guidance was followed without question, there would be insufficient space for the wet concrete to flow between the steel and the formwork. What seems to have happened in many cases is that once the formwork was removed a sand and cement render coat was applied to fill the voids left in the concrete.

There were also quality issues arising from how the concrete was batched, carried and placed in small quantities. An unnamed representative of a concrete mixing plant reported in 1915 that the cheap labour costs meant he saw only one mechanised mixer in Bombay and that the concrete was mixed on the ground, and then placed into small baskets to be carried on the heads of «cooley women» (Twelvetrees 1915, 440).

The Concrete Association of India, formed in 1927 to promote and develop the reinforced concrete market in India, published 39 booklets during the 1930's on subjects like concrete fences and gateposts, cement plastering and concrete roads. Volume 4 «Floors and Footpaths» describes how concrete will keep out rats, and that «concrete pavements are unperishable (sic) and last for ever. They can stand the vicissitudes of the Indian climate and once laid

never need repair» (Anon 7, 1937, 3). Apart from their unrealistic claims, a fundamental problem of these publications is that they suggest building elements can be put together without a proper understanding of the materials, the overall structure or the care needed during the construction. This «kit of parts» approach to building has led to many of the problems that can be seen on reinforced concrete buildings.

The Uses of Reinforced Concrete in India

The majority of contemporary accounts in architectural and engineering journals on the use of reinforced concrete in India refer to its use in buildings, structures and civil engineering works such as roads and bridges. It was also extensively employed for more mundane items such as lamp and fence posts, and railway sleepers (Stokes-Roberts 1910, 39; Anon 8, 1923, 667). There was also mention that India should build reinforced concrete ships for the coastal trade to save on imported steel (Anon 9, 1919, 310).

The following is a summary of buildings and engineering structures and other miscellaneous uses, selected to illustrate the various forms and applications of reinforced concrete. These have been organised into broad categories based on the use of the building and arranged chronologically.

Civil Engineering works

Bridges

The earliest documented reinforced concrete structures in India found to date are two small bridges constructed in 1901 to designs by Major E. R. B. Stokes-Roberts, R.E. (Marsh 1904, 522). Each 9.15m arch was constructed without aggregate using a cement and sand ratio of 1:3 and carried pedestrian and narrow gauge trams across a small, unnamed river.

Less than 10 years later the much larger Afzal Ganj Bridge was built across the Musi River in the centre of Hyderabad. After a flood in 1908 had destroyed the previous masonry bridge a new reinforced concrete structure, designed and built by Messrs. Marland, Price and Co. from Bombay was completed in 1911. It was, at the time, the largest reinforced concrete bridge in India with four elliptical arches that span 16.46m onto piers built off masonry foundations. The arches are between 375 and 600mm deep at the crown and were cast in-situ with a cement: sand: aggregate mix of I: 2:4 and two layers of 25mm square reinforcement bars at 250mm centres supplied by the Indented Bar and Concrete Engineering Co. in London. The approach roads to the bridge are on reinforced concrete boxes grouped together and infilled with lime concrete and stone (Anon 10, 1912, 145).

A number of submersible bridges, i.e. bridges where the road deck was liable to flood during the monsoon were built. The earliest in India is the Manimalai Bridge between Travancore and Cochin in Kerala, built in 1915 with eight 8.5m span reinforced concrete arches (Anon 11, 1955, 41). The first pre-stressed concrete bridge in India is Napier Bridge, built between 1939 and 1943 near the Fort area of Madras. A second bridge, based on the 1939 bowstring girder design, was opened on the 5th February 2000.

Harbour Facilities

The Port of Madras constructed over 1400 metres of wharfing between 1905 and 1910 using pre-cast piles and retaining walls that were driven into the sand. The wharf wall was anchored in place with steel ties that were encased in concrete for corrosion protection. The 31 cranes were each founded on a group of four, 375mm square, driven pre-cast concrete piles (Spring 1911, 427).

Water Tanks and Towers

The first recorded reinforced concrete water tanks were designed in the early 1900's by Major Stokes-Roberts. These had a mass concrete base sitting on the ground and brick walls with reinforcing bars formed into hoops, tied together with telegraph wire, in the bed joints. The tanks were topped with a reinforced concrete dome between 37–50mm thick (Marsh 1904, 524). Included in the article were drawings that showed the timber centring to support

the roof during its construction and a method of removing the props once the concrete has gained strength. As well as demonstrating an awareness of the need to consider the construction process it seems that Stokes-Roberts was keen to use his work as an exemplar for other engineers in India and elsewhere.

The aesthetics of water towers were discussed following a presentation to the Institution of Indian Engineers (Temple 1929, 112). A contribution by G. Bransby Williams, who said he had «probably designed and erected more water towers than anyone else in India», was that it extremely difficult to achieve an aesthetically satisfactory design without making them look «entirely unlike a water tower». An example of this is at Puri where the structure of the tank is hidden behind a «New Delhi style» exterior designed by the PWD architect, J. F. Munnings. These «architectural» water towers were considerably less robust than the more honestly expressed structures. The dome to the Puri tank is a steel frame with a 75mm concrete layer reinforced with a diamond-shaped steel mesh. An even thinner structure is the 55mm thick curved roof to the southern reservoir at Muzaffarpur made by «throwing cement plaster» onto wire mesh fixed to a steel frame (Temple 1929, 118).

Roads

The early concrete roads were unreinforced, such as the road over Law's Bridge in Madras constructed in 1914 that is described as «probably the oldest in India» (Anon 10, 1955, 11). There is however a reference to concrete road in Rangoon, Burma, then within the boundary of British rule in India, said to date from 1907 (Anon 12, 1934, 67). «Concrete Roads in India», published by The Concrete Association of India (CAI) in 1931, promoted the benefits of concrete against other road-building materials and reinforced concrete was and remains the main method of road construction.

Buildings and structures

Housing

The first reinforced concrete buildings were also probably designed and built by Military Engineers and Stokes-Roberts is referred to as the engineer for the posts, beams and rafters on an un-named army barrack constructed prior to 1905, (Winn 1905–7, plate E). The same paper also shows a roof design by Captain Traill, R.E. that combines rafters that were pre-cast on the ground and covered with 50mm thick slabs reinforced with 3mm bars. These slabs were also pre-cast, onto bamboo plastered with mud to provide a level surface, and then covered with oiled paper.

The earliest civilian reinforced concrete buildings were probably built in Bombay. In the suburb of Byculla a four-storey students hostel built in 1907 for the Victoria Jubilee Technical Institute is described as the «earliest reinforced concrete structure in India» (Anon 11, 1955, 11). The Indian practice of Messrs. Taraporvala, Bharoocha & Co. provided the architectural and engineering design.

The Spring Mill Worker's Chawls, Naigum Road, Dadar in Mumbai were built between 1915 and 1917/18 to provide low-rent accommodation for workers at the nearby mill. There are five buildings; each three stories high with rooms arranged each side of a central corridor. Each 3 m × 3.6 m room and 1.35 m deep verandah was intended to house four people with communal toilets and washing facilities in the centre of each block (Anon 4, 1917, 158).

The plan of the buildings is attributed to J. F. Watson, a civil engineer who was serving with the Royal Engineers in France during the construction. It is likely that he prepared the general arrangement drawings and that the unnamed contractor carried out the detailed structural design. The structures are an early form of a reinforced concrete frame with square columns supporting beams that span front to back. The 90mm thick floor is carried on secondary beams, referred to as joists in the article, at 1200 mm centres. The dividing walls between each room, and between the rooms and the communal corridors, are also constructed in concrete. These are only 75 mm thick, with reinforcing bars tied to steel hooks cast into the adjacent beams and columns. A gap has been left to the underside of the beam above to provide cross ventilation. The flats also had two reinforced concrete shelves in each room, so it is possible that the buildings were used to show the potential for what was then a relatively new building material in India. The buildings remain in full use but the structures are now in a poor condition, with extensive areas of

spalled concrete and corroding reinforcement due mainly to the inadequate concrete cover to the reinforcement and a lack of maintenance. A programme of repairs is needed soon to safeguard this important group of buildings.

By the mid 1930's most of the larger apartment blocks in Bombay were reinforced concrete framed structures. Flats designed by G. B. Mhatre at Byculla, Bombay, now called Ready Money Building, were completed in 1935 (Anon 13, 1936). It has r.c. columns, beams and slabs, with the brick walls only acting as partitions between rooms. Mathre studied Architecture in London from 1928–1931 and on his return to India he joined Poonegar and Billimoria (Iyer 2000,10). Poonegar was a civil engineer, so the practice was able to offer a full design service to clients.

Many of the smaller apartment blocks and houses built in the 1930's also made use of reinforced concrete such as The Governor's House, now Raj Bhavan, in Hyderabad by Eric Marrett, 1936.[6]

Offices

Reinforced concrete quickly became established as the preferred method of structuring office floors, and for the larger buildings it was also used to form the main structural frame. Bombay House, Homi Mody Street, Fort, Bombay was built in the early 1920's as the headquarters and offices for the Tata group of companies on an empty site in the centre of Bombay's commercial district. It is a five storey, reinforced concrete framed structure that is externally clad in Malad stone.

Original drawings are dated 11th November 1921 and signed by the architect George Wittet, who joined the Board of Directors of The Tata Engineering Company Ltd. in 1919. Detailed drawings of the reinforcement are also dated November 1921 and signed by N. T. Patel who was likely to have been the project engineer working for Tata.[7] The reinforced concrete frame divides the plan into a grid with columns at about 6m intervals supporting downstand beams, with an intermediate beam in each bay to reduce the span of the 100 – 140mm deep reinforced concrete slabs. Steel trusses and purlins are used to form the pitched roof. The building is founded on reinforced concrete pad footings below the internal columns and strip footings beneath the perimeter columns and the brick or concrete shear walls. The detailing of the reinforcement is typical for buildings of this type and age and is similar to the Hennebique patented system.

Another reinforced concrete framed building is the office of The Associated Cement Companies Ltd. opposite Churchgate Station in Mumbai. This building was the subject of an architectural competition in 1938, with Gregson, Batley & King as the assessors. The winning design by Ballardie, Thompson and Mathews of Calcutta is both a celebration and promotion of cement. The elevations and internal surfaces are finished with a cement render and the floors and stairs had a polished coloured cement or terrazzo finish to the floors. One of the special features was the main curved cantilevered staircase that «in order to illustrate what can be achieved in reinforced concrete technique when carrying out modern design . . . has purposely been made of somewhat intricate construction» (Anon 14, 1938, 24–27).

Many office buildings had load-bearing brick walls supporting the reinforced concrete floors, such as at Kasturi Buildings, Mount Road, Madras, built for The Hindu newspaper. Opened in 1940 the building was designed by H. Fellowes Prynne of the Madras-based architects, Jackson and Barker, with the structural design by N. R. Srinivasan working for the contractor, The Modern Construction Company. The main four-storey elevation has a rendered brick façade with a reinforced concrete cantilevered canopy over the main entrance. Internally the floors are reinforced concrete beams and slabs spanning onto masonry walls, with r.c. columns in one room only to break the spans of the beams in the open-plan Typist's Hall.

Industrial Buildings

One of the earliest reinforced concrete buildings in India is Swan Mills in Bombay. This was constructed in 1905 using stone external walls with r.c. columns internally that support a saw-tooth profiled roof of steel rafters and purlins with 50mm thick mesh reinforced slabs cast onto curved steel formwork (Anon 15, 1906, 10).

Public Buildings

There is no record of when reinforced concrete was first used for buildings such as schools, hospitals, churches or other public buildings but by the 1930's it had become the standard method of constructing many of these larger buildings throughout India.

The Freemason's Hall in Madras is a two-storey structure with load-bearing brick walls and steel beams that support a «Kleine» proprietary first floor and flat roof. The Hall was designed by the Madras-based architectural practice of Jackson and Parker and built by the Raman Menon Construction Company. The cornerstone was laid on 26 February 1923 and the Hall was completed in 1925.[8] The Kleine floor system was invented and patented in 1892 and introduced into Britain in 1896. It used hollow clay blocks laid end to end with thin, longitudinal strips of steel «reinforcement» in mortar filled joints between the blocks. The materials for the Kleine floor were all produced in India and the clay blocks used here were marked «Kollan Tiles, Quilon Tile Works», from Quilon in Kerala. There is no record of an engineer being involved in the building and it is likely that the floors were «designed» by the contractor using load-span tables provided by Kleine.

The J. N. Petit Library on Dadabhai Naoroji Road in Bombay is a rare example of a reinforced concrete extension to an existing building. Opened in 1898, the original pitched, timber roof was replaced by an r.c. floor and flat roof in 1936–38 designed by Tara Poorwalla.[9]

Kacheguda Railway Station in Hyderabad was designed by Vincent Esch in 1914. At a lecture in 1942 Esch admired «how very skilful the Indian craftsmen are with pre-cast and reinforced concrete work, and I think this railway station, designed in Indo-Saracenic style on this principle of construction, is a wonderful example of their skill» (Esch, 1942, 50). He also wrote «This architectural gem . . . is entirely built in pre-cast re-enforced concrete» (Tillotson 1993, 33). While Esch was right to praise the quality of the building, he is not correct in the description of its structure.

The ground floor walls and columns have a rendered finish, but from their size it is likely they are built in brickwork, and the underside of the first floor has steel beams supporting an in-situ reinforced concrete slab. Externally the absence of obvious joints in the projecting chajjas suggests these are also in-situ. The pre-cast elements are all likely to be non-structural such are the jalis, pierced parapets and internal screens.

Repair Works

The use of reinforced concrete in repairing India's historic buildings is now widespread but its use is not new. One of the largest concrete repairs was in 1936–37 on the Gol Gumbad in Bijapur. There, the Archaeological Survey of India found that the 2.6 metre thick, 41 metre diameter dome had large cracks reported to be caused by thermal movements. The repair involved stitching across the largest cracks and wrapping the outside face with bars that were then covered with a sprayed sand-cement mix (Dikshit 1940, 16).

Decorative Reinforced Concrete

The use of reinforced concrete for non-structural elements has already been discussed at Kacheguda Station, above. A totally Indian use of the material, also in Hyderabad is the jails, or pierced screens, that surround the courtyard entrances to the Gosha Mahal, or Freemason's Lodge. These were made circa 1934 of pre-cast panels reinforced with 5mm diameter steel rods under the supervision of Mehar Ali Fazil, the Superintending Engineer for the Hyderabad City Improvement Board (Anon 16, 1936, v).

Conclusions

The first uses of reinforced concrete in India were by British military engineers at the start of the 20th century. Officers from The Royal Engineers designed simple structures based on information from technical journals, patents from European companies and their own tests and trials. The first decades of the 20th century can be seen as partly a period of experimentation and learning, both for the engineers and for the Indian builders who had to learn new skills and techniques. Private architectural and engineering practices soon overtook the military engineers, and the governments Public Works

Department in the design and construction of reinforced concrete.

The first buildings used materials imported from the UK and it was not until the late 1920's that India had sufficient factories to produce the quantities of the cement and reinforcing bars needed by the building industry. Once this industrial infrastructure was in place the number of reinforced concrete buildings and the companies able to design and build in the material rapidly increased. The construction industry was steered towards using reinforced concrete by the strong promotion of The Concrete Association of India and The Associated Cement Companies formed from the various cement producing companies.

In common with other developing countries the low labour costs and the plentiful supply of cheap labour were also important and meant that reinforced concrete was, and still is, widely used for medium to large-scale constructions.

The growth in reinforced concrete construction during the 1920's and 1930's was largely an urban one, based on the demand for larger scale buildings that could not be structured using traditional materials. The centralised, factory-based production of cement and steel also tended to concentrate the use of reinforced concrete in the larger cities with their established transport links.

The use of reinforced concrete followed developments in the UK, where there was a more cautious approach to the potential uses of the material than elsewhere in Europe. As a result there was little of the engineering innovation in India that had existed during the 19th century expansion of the country's rail network. This conservatism was misguided in one key area —the adoption of British Standards without the necessary changes to suit the Indian climate. When this is combined with the use of poorly trained workers, a lack of adequate supervision of the construction on many buildings, and a subsequent lack of maintenance, the results are the commonly seen problems of staining, spalling concrete and corroding reinforcement on many of these buildings.

Notes

1. Advertisements in Kotasthane, Reinforced Cement Concrete Construction.
2. Interview with S. A. Reddi: Deputy Director of Gammon India Limited, February 2001.
3. Gammon, John c. 1913. Reinforced Concrete Design Simplified. Bombay. Crosby Lockwood and Sons.
4. Interview with S. A. Reddi.
5. Interview with N. B. Hadker: Director of Sterling Engineering Consultancy Limited. February 2001.
6. From a discussion with Ravindra Gundu Rao, Mumbai 2001.
7. From drawings in the Bombay House archive seen February 2001
8. Discussion with Professor M S Mathews, Chennai, March 2001
9. From a discussion with Ravindra Gundu Rao, Mumbai, February 2001.

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The structural development of masonry domes in India

Stuart Tappin

This paper researches the origins, structural development and construction of masonry domes in India. It investigates where the structural engineering knowledge of the original builders came from and how successfully that knowledge was applied. We will also look at the choices that had to be made with materials and methods of construction.

The period under review covers Islamic rule over northern and central India from the late 12th century to the mid 18th century. New types of buildings and structural forms came with the new rulers in particular, for this study, the domed tomb. How Hindu masons, experienced only in trabeate construction, responded to these new structural forms is a key part the synthesis of styles that created a wholly new and original architecture.

The choice here of a particular building has been made on the basis of it marking an important structural development in terms of form, scale or technical achievement. Many of the key buildings in the evolution and development of domes are in Delhi and I have concentrated on these along with the monuments in Agra and Bijapur.

Apart from the buildings themselves, the other sources of information are discussions with Indian architects and engineers and study of 16th century paintings. Where no information is available, such as to how the domes were constructed, assumptions have been made based on comparisons with the building of modern masonry structures in India, which still generally relies on non-mechanised methods of building and documented practice in Europe during the period under study.

Islamic Prototypes

In Syria the classical Roman temples and mausolea became the model for builders who created churches or memorials to house the body or relics of Christian saints or biblical character, or to mark a particular event (Hillenbrand 1984, 254). These were generally small in scale and used a variety of plan-forms; square, cruciform, polygonal or circular. The small size meant that the structural stability of the dome could be achieved by copying existing buildings.

At the centre of Byzantine in Istanbul the understanding of structures continued to develop and led to buildings such as the Church of Hagia Sophia. Built between 532 and 537, this has a shallow brick dome, approximately 32 metres in diameter. Its builders understood the need to resist the outward thrusts from the dome and used iron cramps between the marble blocks that form the cornice to create a continuous tension ring at the springing point of the dome (Mainstone [1975] 1988, 123). One potential source of this understanding was the continuation of the tradition of building masonry domes that had existed under the Romans. The other reference was translations of the scientific writings of Euclid,

Ptolemy and others, and the Roman architect Vitruvius. These, along with Arabic works on geometry and algebra, were later translated into Latin in the 11th and 12th centuries to form part of the basis of knowledge of the Middle Age cathedral builders in Europe (Gimpel 1993, 100).

The symbolic importance of the dome in Islam was established in the building of the Dome of the Rock in Jerusalem. Completed in 691, the dome is about 20 metres in diameter, and consists of two hemispherical wooden frames supported on a circular colonnade of masonry piers and columns surrounded by two octagonal ambulatories (Eltinghausen and Graber 1987, 28).

With the spread of Islam by nomadic tribes in central and west Asia, these Christian prototypes became mixed with their own indigenous portable structures to produce new building types. The pre-Islamic burial practices of these tribes probably developed out of traditional customs where the deceased was covered with a tent (Mark 1995, 12). Once they had adopted Islam their burial practices were developed to produce masonry mausolea, in line with passages from The Koran, such as Sutha 18, The Cave. This tells of seven youths who are guided by Allah away from a city to a refuge in a cave. After their death the people argued among themselves, «and those that were to win said: "Let us build a place of worship over them."» (Dawood [1956] 1997, 205). The symbolism of the domed temples and churches of the Romans and Christians were obvious models for Islamic tombs and is alluded to in the description of heaven, in Sutha 21:25, spread «like a canopy». (Dawood 1997, 229)

The earliest surviving Islamic tomb is that of Qubbat-al Sulaibiya at Samarra, built circa 892. (Michell [1995] 1996, 250). This is octagonal on plan with a double-height central chamber that was originally covered with a dome raised on a drum. Another important tomb is the early 10th century Tomb of Isma'il the Samanid in Bukhara (Tadgell 1990, 154). It is square on plan with slightly tapering brick walls with a seven metre diameter dome supported across each of the corners by brick squinch arches buttressed by a radial half-arch.

A structural form that was to have a significant influence in India is the double-dome. The earliest known masonry double domes are a pair of 11th century tombs at Kharraqan (Eltinghausen and Graber 1987, 269). In Iran the double dome reached its apogee in the Mausoleum of Oljeitu at Sultaniya. Built between 1304 and 1315, the inner of the two interconnected brick domes has an internal diameter of 26 metres (Hillenbrand 1984, 199; Maidstone 1998, 124).

In Iran the emphasis on height led to tomb towers like that at Gunbad-i Qabus built in 1007 which reached over 51 metres above the ground and is capped with a conical roof, based in form on the tents used by the nomadic Seljuks then ruling from Iran to the eastern Mediterranean (Michell 1996, 253). In 14th and 15th century Samarkand the desire among the rulers and noblemen to build higher tombs for themselves led to domes on the top of elongated, cylindrical, masonry drums, with a dome at the base of the tower to maintain the internal proportions. The Gur-i Amir was built circa 1404 for Timur, a descendent of the Mongol chieftain Genghis Khan (Hillenbrand 1984, 214). This used a framework of timber built off the internal dome that served to help construct and provide permanent support to the outer, bulbous dome.

In structural terms the raising of the outer dome on an elongated drum increases the risk of movements in the drum. To resist these outward forces from

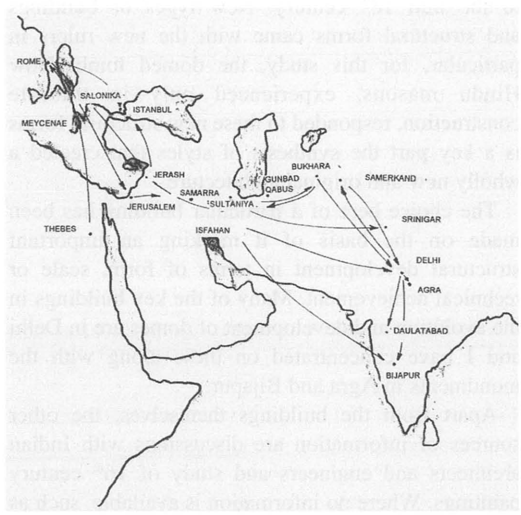


Figure 1
The principal routes for the movement of structural influences on domes in India

causing cracks required the introduction of a material capable of resisting tensile forces (Lewcock 1996, 143). There are references to the use of timber reinforcement rings at the base of the dome, or iron cramps set into stones so that a continuous ring, or reinforced stone chain is formed. For the Gur-i Amir, a cross section through the two domes shows radial tie bars built into the wall at the base of the outer dome (Cresswell 1914, 94). This is a sophisticated use of materials, but this system is not mentioned in any reference to double domes in India.

Who were the designers?

From looking at the masonry domed buildings we can see that they were built with durable materials, we can deduce that the designers and builders knew how to use these materials and that they had an understanding of the importance of proportion and geometry to produce a structure that could support all the loads. There is, however, hardly any information on those involved.

The titles of people engaged in the design and construction have been given a number of different translations. One source says «darogha "imarat"» translates as chief architect, another, in relation to the title for Mir Abdul Karim at the Taj Mahal, calls him the Superintendent of Buildings (Qaisar 1988, 10; Begley 1989, 227).

Qaisar considers the roles of people involved in the construction of a building. From his description the architect/engineer [me'mar/muhandis] was involved in choosing the site and then prepared a tarah, or plan, of the proposed building for the client. More than one design could be presented and for part of Lahore Fort a tarah prepared by the me'ma*r* was chosen by Shah Jahan and «was handed over to muhandis to carry out the work accordingly» (Qaisar 1988, 37).

The documentation on the building of the Taj Mahal offers a rare, but limited, glimpse of those involved in its building. Ustad Ahmad is described by his son as having «followed the profession of Science» and was «Chief Architect [me'mar-i-kull] in this court», i.e. of the emperor Shah Jahan (Begley 1989, 267 & 290). As well as being an architect, Ahmad was recognised as an outstanding astronomer, engineer and mathematician. Mukarramat Khan «Minister of Royal Works» to Shah Jahan is described as an administrator, not an architect, (Begley 1989, 282) but it is likely that his understanding of mathematics and practical matters would have led him to be involved in aspects of the design and construction. Mir Abdul Karim had been chief architect for Shah Jahan's father, Jahangir. Within a few months of Mumtaz Mahal's death he was transferred from Lahore to Agra to become Superintendent of Buildings. This suggests a specific role, equivalent to a modern-day project manager, appointed by the client to oversee the works which Tavernier said involved twenty thousand men over 22 years (Begley 1989, 227).

Building Materials

The main materials used in the construction of the structure of the domes were stone, brick and mortar, with ironwork for dowels and cramps. Timber and bamboo was used for the scaffold and centring that provided the temporary support to the dome during the construction.

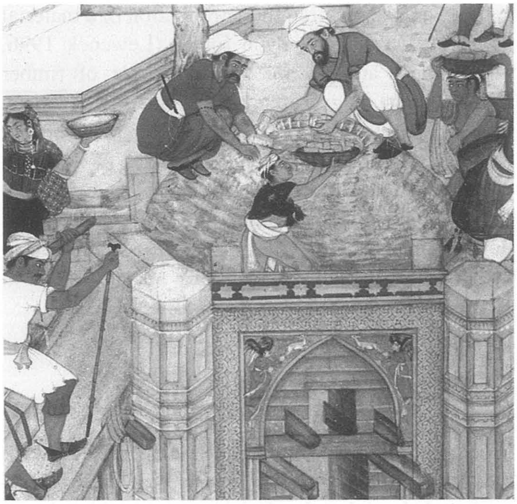
Stone

Stone was widely used as a building material in pre-Islamic Indian buildings. The first Islamic buildings at the Qutb site in Delhi were constructed by captured masons using stones from the remains of the twenty-seven demolished Hindu and Jain temples. New stonework was used for the extension to the mosque, shaped into rectangular blocks and laid horizontally with the corbelled edges cut back to form the arch-shaped openings.

A masonry building could be constructed more quickly and cheaply if undressed stonework was used on one or both faces. The walls, arches and half-domes that remain at the late 13th century tomb of Balban use coarsely cut stones that would have needed an applied finish. Two centuries later the prolific building of tombs during the Lodi dynasty would have put great demands on the availability of skilled masons and of good quality stone. Instead, many of the tombs from the mid-15th century to the early 16th century are built from roughly dressed stonework with a rendered internal and external finish.

Dressed stonework was used externally and internally for most of the important buildings, such as the surviving walls of Iltutmish's tomb, built circa 1235. Here the stone outer and inner faces of the walls were bonded together with a core of roughly cut stones or broken bricks (Brown 1997, 17). This allowed the use cheaper materials and labour for the unseen parts of the structure.

Where the stonework forms the exposed faces of a dome, it needs to be carefully cut in all three dimensions to form the voussoir blocks. This requires an understanding of three-dimensional geometry by the masons, with the sides and exposed face(s) cut to the correct profile for the size of the dome. The first use of a dressed stone dome in India is for the Alai Dawarza in 1311. It is likely that the masons who had this knowledge came from the break up of the Seljuk empire to the west caused by the «total war» raged by Genghis Khan and his decedents in the 13th century (Hillenbrand 1999, 96).



Picture 1
Building Agra Fort

Brick

The use of brickwork is mentioned during the 14th century building works at Hauz Khas and was widely used for smaller arches and domes from the 16th century (Rani 1991, 89). Examples can be seen at the tomb of Humayun or the 18th century tomb of Safdar Jang. The bricks are all rectangular in shape with tapered mortar joints used to form the required curvature.

Three types of bricks are mentioned in the 16th century; baked, half-baked and unbaked (Qaisar 1988, 16). The lesser quality bricks may have been used for the temporary centering seen in the Akbarnama. Nath refers to a standard Mughal brick size of 8" × 7 $^1/_2$" × 1 $^3/_4$", but that the Taj Mahal was built using a thinner size, 7" × 4 $^1/_2$" × 1" « . . . to allow the mortar to occupy a greater part of the volume» (Nath 1972, 79). It is not clear what is the basis of this comment since, structurally, the greater use of mortar increases the risk of cracks developing as the mortar dries and shrinks. Nath also mentions that the bricks for the foundations, which extend well below the level of the adjacent River Yamuna, were dipped into liquid fat to «make them waterproof» (Nath 1972, 79).

Mortar

Hindu architecture of the pre-Islamic period appears to have used mortar as little as possible (Qaisar 1988, 18) and the stonework in the first building at Qutb is also dry bedded. By the early 13th century the buildings made use of rekhta, meaning either mortar or plaster, in the construction (Qaisar 1988, 19). Mortars made use of lime mixed with a range of additives to improve its workability, durability and setting properties. These included jaggery, a fermented nut whose use has been revived in recent years for conservation work, and surkhi —or crushed brick— as an artificial pozzolana.

Iron

The structural use of iron in masonry was fundamental in restraining the high outward forces generated in the larger domes. The use of iron cramps between stones was already known in pre-Muslim India, and cramps between adjacent stones were used to create what we today call hoop reinforcement in order to restrain the base of domes (Qaisar 1988, 22). Iron dowels were used to connect vertical elements

such as the individual stones within columns, and cramps employed to secure the facing stones back to the core of the wall, such as at Humayun's Tomb and the Taj Mahal.

Timber and Bamboo

This was used to form access ramps from ground level to the level of construction, and to provide temporary support to the centering. There is no evidence of timber being used as part of the permanent structure.

Methods of Construction

One of the best sources of information about how arches and domes were built is the Akbarnama, or Life of Akbar, a series of paintings from the late 16th century that chronicle the life of the third Mughal emperor.[1] None of the buildings in the Akbarnama, or other contemporary paintings, have been specifically identified but they do show the organisation of the site, the works of different trades and their methods of working.

There is little evidence of off-site working or pre-fabrication. Large sections of stone were brought to site where they were split to the required size using driven iron wedges. The larger stones were then secured with ropes and manhandled using temporary timber ramps to where the masons were working. This method is clearly limited by what it is physically possible to carry. In one illustration four men are carrying a block of stone about 1500 mm long × 300 mm square in section, a load of about 100 kgs per man.

Some illustrations tell us about actual methods of construction. An arch to a gateway is shown with two piers of bricks and a timber lintel to support the centring used to construct the structural arch. The lintel allows access through the gate while it is being built. Above the gate a small brick dome is being constructed with the bricks laid in concentric rings to eliminate the need for centering. Examples of this type of construction can be seen at Humayun's Tomb and Safdar Jang's Tomb.

For larger domes, where the thickness of the structure is greater a different approach is required. The dome of the Gol Gumbad in Bijapur is one of the largest masonry domes in the world with an internal diameter of 41.15 m that is 2.6 metres wide at the base. The dome is built off eight intersecting arches that span across the corners of the square to support the dome and rise to 37m above the crypt floor level (Reuban 1947, 39–47).

There are no large forests around Bijapur, so the large quantity of timber required for the centering to support the arches during the construction would have been difficult and expensive to procure. An alternative is to use brick centering as the temporary support to the arches. Once the permanent arches and pendentives were in place the vertical base of the dome could be formed. This helped to tie the top of the arches together and provided the dead load to the top of the walls to reduce the outward thrusts from the arches so that the brick centring could be removed. It is possible that this removed material was used in the construction of the upper part of the dome that could have been built off temporary formwork supported on the balcony around the base of the dome.

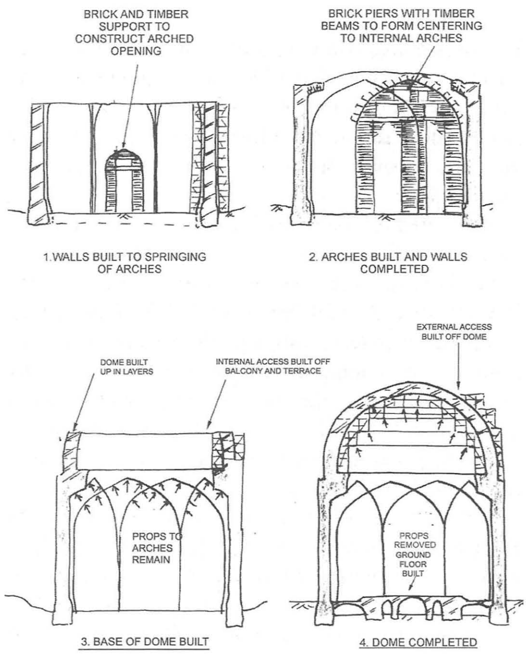
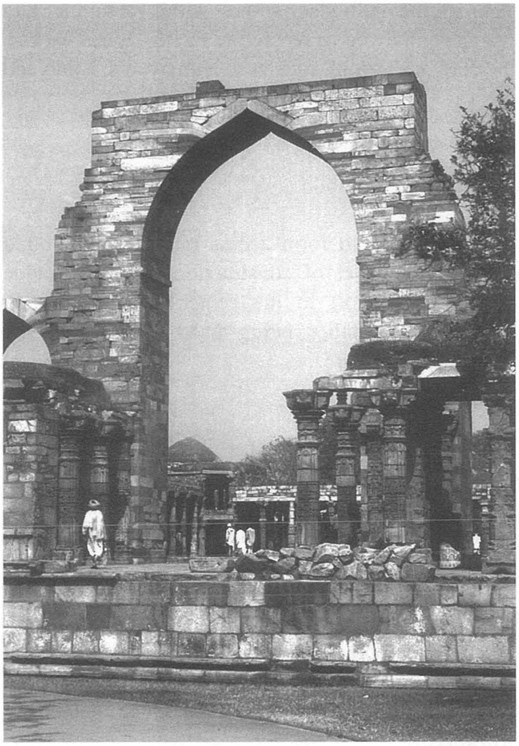


Figure 2
The Assumed Sequence of Construction of the Gol Gumbad

At the Taj Mahal Tavernier reported that «It is said that the scaffolding . . . for the want of wood . . . had to be made of brick» (Begley 1989, 298). Given the scale and geometry of the building it is very unlikely that brickwork alone would have been used for temporary support during the construction. Scaffolding was used for a variety of purposes and timber or bamboo scaffolding would have been used externally to provide access to place the marble cladding. It could also have provided the temporary support to the structure during construction and it may be that a combination of brick piers and wooden scaffolding was used. Once the inner dome was formed it could be used to support the wooden framework needed to create the outer dome.



Picture 2
Remains of the Quwwat-al-Islam Mosque, Delhi

Masonry Domes in India

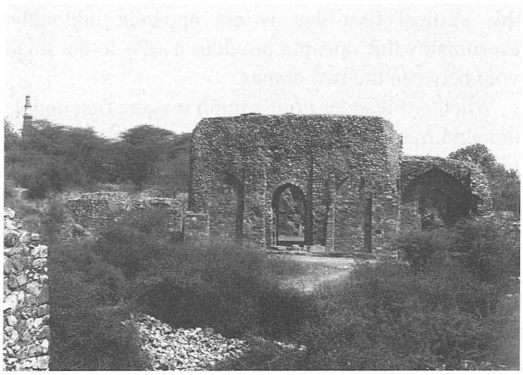
The first key buildings date from the end of the 12th century with the capture of Delhi in 1192 by the forces of the Afghan Turk, Muhammad of Ghor (Sharma 1990, 52). The leader of the invading army, Qutb-ud-Din Aybak, was placed in charge of the conquered areas and established Delhi as his capital. In the same year a mosque was built, later to be called the Quwwat-al-Islam or Might of Islam which, as we have seen, used stonework from destroyed Hindu and Jain temples; re-laid by indigenous masons following their traditional technique of beam and post construction.

About eight kilometres from the mosque is Sultan Ghari's tomb. This is the first major Islamic tomb in India, built by Iltutmish for his son and heir Nasir-ud-Din who died in 1229 (Sharma 68). This is set within a walled enclosure with the tomb chamber in the centre of the compound below an octagonal plinth. The original roof to the chamber has been replaced by a flat surface, but it may have been similar in form to the trabeate construction of the square pyramidal roofs on the outer walls.

The first use of true arches is the tomb of Sultan Balban, who died in 1287, and two smaller adjacent tombs, about 500 m southeast of the mosque (Rani 1999, 6). The main tomb is about 11.5 m square with its walls constructed in roughly coursed stone bound in a mortar. The arches are either made in the same roughly cut blocks or with dressed stonework. On the west wall of the main building, in the direction of Mecca, is the remains of a half-domed prayer niche. The roof of the tomb to the south, known as that of Khan Shahid is similar in outline to the roofs on the tomb of Sultan Ghari but its structure relies on

Picture 3
Courtyard of Sultan Ghari's Tomb, Delhi

arching action to create a small dome with the external finish built up in render. These structures stand apart from the general developments in arcuate construction. Similarities in the three buildings suggest that the same masons were employed, and perhaps after their patron died they moved elsewhere. As the tombs lie outside of the mosque complex and the structures, when completed, were covered with a rendered finish the use of arcuate construction was not adopted by other masons.



Picture 4
Remains of Balban's Tomb, Delhi

The Alai Darwaza, completed in 1311 as the south gate to the Quwwat-al-Islam mosque is the first building to use and express true arches and the central dome. The arches are formed from stone voussoirs and similar arches are used internally to form the transition from a square to an octagonal plan. The final transition to a 16–sided polygon at the base of the dome is by small, corbelled brackets.

The dome for the tomb that Ghiyas-ud-Din Tughluq built for himself before his death in 1325 rises clear above the massive sloping walls. Internally the dome has alternate rings of shallow and deep stones, with the shallow layers bonded into the core of the dome to produce a more robust structure. Within the same compound is the tomb of Zafar Khan, built by his father Ghiyas-ud-Din, notable for it's octagonal shaped chamber and ambulatory.

Ghiyas-ud-Din was succeeded by his son Muhammad Tughluq who in 1328–29 moved his capital to Daulatabad, 960 kms to the south of Delhi,

Picture 5
Alai Dawaza, Delhi

to consolidate his authority in the Deccan, only to return soon after (Brown [1956] 1997, 22). A consequence of this move was the dispersal from the Delhi region of the skilled masons and artisans. This loss had an impact on the construction of buildings under the next ruler, Firoz Shah Tughluq. In place of carefully cut stones that formed both the structure and finishes, the buildings from the late 14th century used roughly shaped stones for the arches and the domes, which were then covered with render. This can be seen at the Khirki Masjid, built circa 1375 and the tomb of Firoz Shah, who died in 1388.

The reduction in masonry skills would have been accompanied by a loss in the understanding of how to structure the buildings. In its place the builders would have simply copied what had been built before. As structures they have survived due to the massiveness of the walls that support the vertical and horizontal loads from the dome. One building of this period that is stylistically important is the tomb of Khan-i-Jahan Tilangani, the prime minister of Firoz Shah. Built circa 1368, this, despite the tomb of Zafar Khan mentioned above, is generally referred to as the first octagonal tomb in Delhi with the domed central chamber surrounded by an ambulatory verandah with three arched openings on each facet (Rani 1991, 51; Tadgell [1990] 1995, 170).

Picture 6
Khirki Masjid, Delhi

The building skills that were re-learnt during the second half of the 14th century were lost again following the invasion of Delhi in 1398 by the army of Timur (Rani 1991,116). A grandson of Genghis Khan, he sacked Delhi and took artists and craftsmen back to build in his capital, Samarkand (Brown [1956] 1997, 25). The Tughluq dynasty ended soon after and this was followed in 1414 by the Sayyids, and from 1451 to 1526 by the Lodis. There are no significant differences, or major structural developments in the buildings of these two dynasties. Instead, there was a great proliferation of tomb building that reflected the Lodi's Afghan origins where a brotherhood of nobles was commonplace and the king was first among equals rather than the absolute ruler. There was however a hierarchy in terms of plan-form, with octagons for royal tombs, and square for nobles and others of high rank.[2]

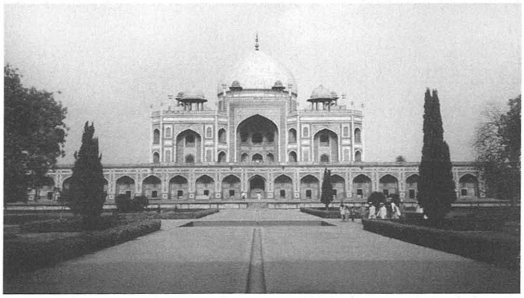
One structural question from this period concerns the introduction of the double dome. The tomb of Sikander Lodi, built 1517–18, is referred to as the first double-dome in India, but the section through the building from Tadgell shows only a single dome (Brown 27; Tadgell 162). The interior of the tomb is dimly lit (some doors have been infilled with brick) but the dome does spring from a level where externally the sides of the dome are vertical. There is also what appears to be a partly blocked opening on this vertical face that is not apparent internally. Presumably this opening provides access to the small void between the two domes.

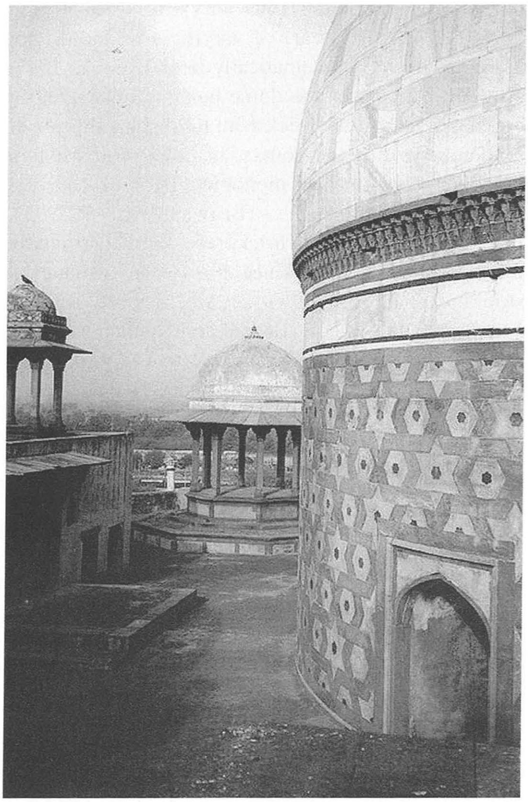
Whether Sikander Lodi's tomb was the first double dome in India is less certain. The tomb built by Zain-ul-Abidin c.1465 for his mother at Zaina Kadal in Srinigar in Kashmir is a brick structure with double domes over the central and perimeter chambers (Agrawal 1988, 168). In Delhi, Sabz Burj has a shallow inner dome and an outer dome raised on an extended drum in the style of the early 15th century tombs at Samarkand. Written sources place this in the early Mughal period of1530–40 (Koch 1991, 36), but it may be over one century earlier.[3]

The Lodi period ended following defeat by Babur, the first Mughal emperor. Babur was descended through his father from Timur and through his mother from Genghis Khan (Koch 1991,10). He died in 1531 and was buried in a simple grave in Kabul. His son, Humayun, ruled between 1531–40 and 1545–56 and his tomb is the first major Mughal building. It was built between 1562 and 1571 early in the reign of his son, Akbar, to a design by Mirak Mirza Ghiyas, an architect from Persia (Brown [1956] 1997, 90). This has a double dome above an octagonal central chamber that is about 15m from side to side. At roof level the small domed kiosks, or «chattri», are constructed in brick and clad externally in stone and rendered on the underside.

It is likely that the main structure of the tomb was also built from brickwork that was then clad with sandstone and marble. The outer surface of the dome has alternate layers of wide and narrow blocks of marble to help bond the cladding to the structural core. The use of iron cramps to tie the facing stone to the core of the wall can be deduced from the characteristic corrosion-related damage at the corner

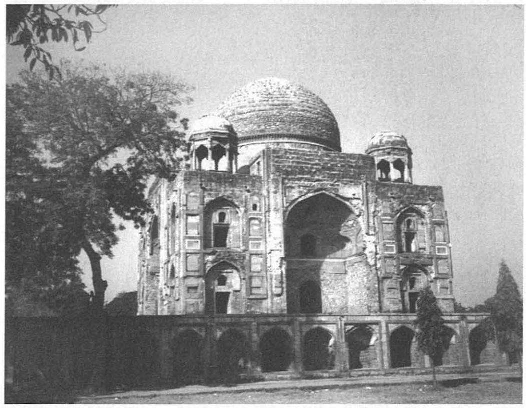
of a number of stones above the entrance portal. There must also be a system of ties around the base of the outer dome to resist the outward forces acting on the top of the drum. It may be that the stones in the horizontal band of marble at the top of the drum are connected by iron cramps to form a continuous tension ring.





Picture 7
Humayun's Tomb, Delhi

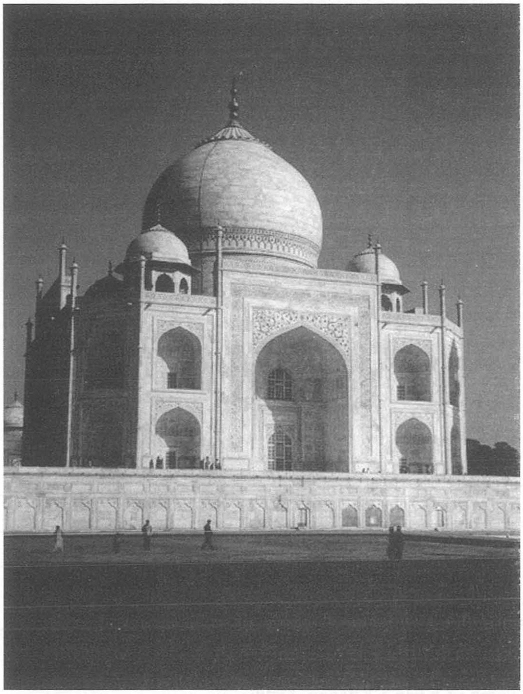
In the same part of Delhi is the tomb of Khan-i-Khanan who died in 1627, the same year as the following emperor, Jahangir. The stripping of large amounts of the sandstone and marble in the 18th century to clad Safdar Jang's tomb has revealed a brick structure with a brick double-dome.



Picture 8
Tomb of Khan-i-Khanan, Delhi

The Taj Mahal at Agra is also a brick structure clad mainly in marble, with sandstone to the half-hidden areas at roof level. Work began in 1632, the year after the death of Mumtaz Mahal, a wife of the emperor Shah Jahan. Much of the tomb was complete four years later and by 1643 the entire complex of buildings and gardens was virtually finished (Asher 1992, 212). It is founded on a series of brick wells that were filled with rubble bound in a lime mortar. The areas between the wells were then dug out and filled with stone and mortar (Nath 1972, 79). These footings pass through approximately 19m of soft alluvial deposits to bear onto a seven metre thick layer of sandstone overlaying clay. The internal dome is 22 metres in diameter and three metres thick. Above this the five metre thick walls to the drum support the outer dome that encloses a void over 30 m high. A summary of how the Taj Mahal works as a structure is shown below.

In Bijapur, the tomb Muhammad Adil Shah built for himself before he died in 1656 is now referred to as the Gol Gumbad, or Round Dome. This has one of



Picture 9
Taj Mahal, Agra

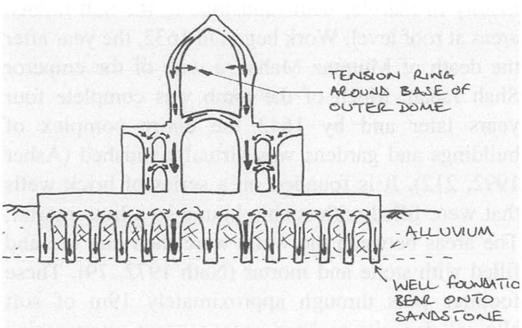
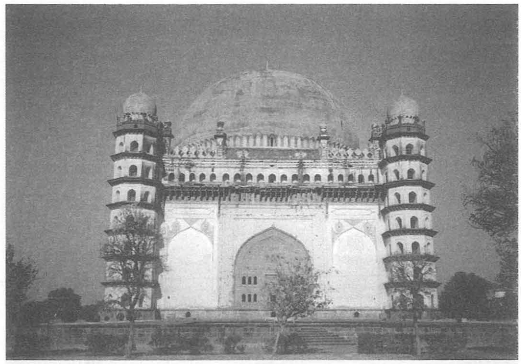


Figure 3
Structural Summary of the Taj Mahal

the largest masonry domes in the world with an internal diameter of 41.15 metres that rises to 54.25 metres above the floor. The base of the dome is approximately 2.6 metres thick.

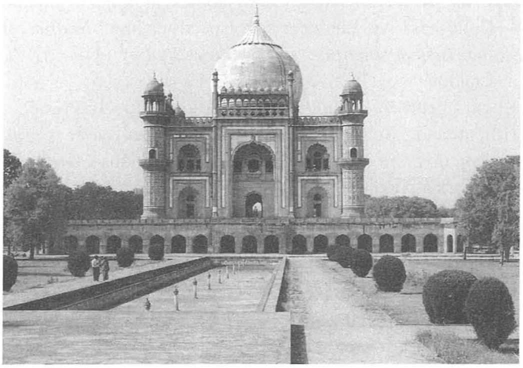


Picture 10
Gol Gumbad, Bijapur

The dome is rendered on both faces. Reuben says he saw it was constructed in brickwork «laid flat in lime mortar . . . joints (that vary) from 25–50 mm thick . . . The bricks are of varying size and do not appear to be very systematically laid» (Reuban 1947, 46). Brown talks of the dome being «constructed in horizontal courses of brick with a substantial layer of mortar between each course, in other words it is a homogeneous shell or monobloc (sic) of concrete reinforced with bricks . . . » (Brown [1956] 1997, 77). It is unlikely that the bricks are laid horizontally throughout the dome, since this would produce a structure that acts more as a series of corbels. Presumably, what both Brown and Reuben saw was towards the base of the dome and that higher up the brick courses are inclined to the inside face so that the layers acted as self-stable compression rings during the construction.

Safdar Jang's tomb in Delhi built 1753–54 was the last major Islamic tomb to be built in India. It is a brick structure that is clad externally in sandstone and marble, and rendered internally. The shallow domes to the chambers around the perimeter of the plinth follow the traditional form of concentric brick rings. The central dome is described as a triple dome, with two «flattish» inner brick domes and an outer bulbous marble dome (Beglar 1874, 76), but no drawings have been found to verify this. It is unlikely that the marble acts alone as a thin shell since its geometry suggests it would collapse under its own self-weight. Instead it seems more likely that the marble is attached to the outer of two brick domes, and there may be a small

domed void between the outer brick dome and the marble lotus leaf finial.



Picture 11
Safdar Jang's Tomb, Delhi

Some Common Structural Problems

The proliferation of dome building from the mid-15th century would have required an increase in the number of masons to build the structures. Inevitably some of these domes were built by masons who copied the form of existing buildings without understanding the structural principles. A common problem with the Lodi-era tombs is an outward spreading of the octagonal verandah at eaves level, caused by the horizontal forces in the arches and vaults that form the verandah roof. These movements can be seen in a circumferential crack at the mid-point of the ceiling and rotation of the outer piers of a number of tombs. This movement probably occurred early in the life of the building as the structure adjusted to reach a state of equilibrium.

There are generally few signs of structural problems resulting from the horizontal forces in the central dome. The early square domes the walls are sufficiently massive to resist these loads and in octagonal tombs the verandah will act as a partial buttress to the central dome. For larger structures, like Humayun's Tomb, the walls of the surrounding chambers resist the forces from the inner dome. The lack of significant vertical cracks at the top of the drum, or radial cracks in the lower part of the dome suggests that where a dome was raised onto a drum, the need to resist the horizontal forces generated was understood.

Masonry, like all materials will expand and contract with changes in its temperature. A structure composed of small elements of stone or brick in a lime mortar will move as a result of thermal changes, but generally the cracks that result will be spread evenly over the whole of the structure and consequently small in size. A large monolithic structure will tend to produce larger cracks that concentrate along lines of weakness. This seems to have been the cause of the radial cracks to the dome of the Gol Gumbad. It was repaired in 1936–37 by spraying concrete to reinforcement fixed to the outside face to help tie the cracked segments of the dome together (Dikshit 1940, 16).

Conclusions

The domes of India are a unique synthesis of Islamic and Hindu influences. Their historical, architectural and structural importance is recognised by having the Taj Mahal, Humayun's Tomb and the Qutb Minar complex on the list of World Heritage sites. As important from a construction viewpoint is the Gol Gumbad in Bijapur that in scale ranks alongside the Pantheon and St Peter's Cathedral in Rome, and Santa Maria del Fiore in Florence.

The early buildings were built by Hindu masons using their traditional trabeate methods of construction. The knowledge of how to build true arches and domes, and effect the transition from a square or octagonal chamber to the base of the dome, came with links central Asia. Other design influences such as the plan-form, double domes and the placing of tombs within larger landscapes also came from these areas and Persia.

A number of the less well-known buildings and structures are in a poor condition, either because of neglect or ill-conceived repairs. Often these repairs are carried out with good intentions but without understanding how the structure was originally intended to work, how it may now be working and what, if any, repairs are needed. At present the building conservation movement in India is almost wholly composed of architects. If these domes and other examples of India's built cultural heritage are to

be handed on to future generations it is important that suitably experienced engineers also take an active role in their conservation.

NOTES

1. The Akbarnama in the Victoria and Albert Museum's collection has recently been described in «Painting for the Mughal Emperor: The Art of the Book 1500–1600» by Susan Stronge, V&A Publications, 2000.
2. From «Visions in Marble», lecture by Catherine Asher at the V&A Museum, London, 1997.
3. From a discussion with Dr Agrawal, Director (Museums and Projects) Archaeological Survey of India at New Delhi in April 2000 who gives a date of circa 1426.

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The geometer and the cathedral

J. L. Taupin

La Géométrie est une science de l'expérience (Michel Cassé).

Do we grant enough consideration to the equilibrium that has kept cathedrals standing for centuries ? Ceremony or meeting organizers seem confident when gathering thousands of people under these vaults spanning 12 meters or more at a height of 30 or 40 meters, which stand thanks to the mutual thrust hundreds of stone blocks exert on each other. Do we understand through which mental processes those monumental monsters acquired such a standing and lasting privilege ? Do we realize that the stability of such a heavy stony sky stems from an exact choice of the right geometrical shape ?

The question is solved before even being asked, since —as we all know— technology is a privilege of present modern times. No science before Newton, neither before Galileo . . . Thus uttering that: «the cathedral's roots lie in empiricism, or the cathedral results from a series of experiments» is to be regarded as a poor answer. Can we imagine people pursuing the best use and effectiveness of their means, at the same time expecting unlikely benefits from random casualties ?

The term «the Middle Ages» suggests a mere and mediocre intermission. That a medieval science could have existed in the Middle Ages in Western Europe is a possibility widely underevaluated in what is commonly pictured of Europe's 12th and 13th centuries. On the contrary, here, we do assume that «the Middle Ages» found its Mechanics in its Geometry. We suggest that its Mathematics lies in the substance of its major architectural works.

In Byzantium and Baghdad, memories of Alexandria's scientific, technical and intellectual knowledge were carefully kept. No inpenetrable border existed in these times moved by antagonisms and covetousness. Trading dealt not only with goods, but also with pictures and ideas. Amalfi and Salerno, Pisa, Genova and Venice collected messages from overseas. Close by, al-Andaluz —Cordoba, Toledo, Zaragoza— gave access to the Omeyad and Abbassid cultures full of antique thoughts (greek, indian, mesopotamian). Palermo was a crossway of cultures. Expeditions of Frankish people on their way through Constantinople to the Holly Land discovered models and arguments they promptly reinvested in material organization, in military and building activities. Fast technical percolations through the whole Mediterranean Sea remind us that mental communication grows in proportion to the material difficulty of communication.

In Western Europe fed with a utilitarian and mixed tradition, the desire of exploring pushed some individuals on the roads, watched closely by more or less open-minded people among their fellow citizens, or on the contrary entrusted by them.

An Architecture of «Arceaux»- The *right* design for an Arch

In french crosswords: «plus fort s'il est brisé».

Bits of receipts and of arguments of medieval builders still remain: Hontanon, Aranda, Derand, Belidor, Blondel, Viollet-le-Duc . . . state a rule: chords underlying three parts cut in a segment of a circle extending between two supports, have determined lenghth and pit: their lenghth duplicated downward along their own axis indicates the right thickness to be given to the bearing walls . . . Absurd says Belidor, since neither weight and thickness of the arch nor how high the wall could be, have been taken into account ! But when considering the pit of the two chords, looking at them as a representation of the tangents at the springings of the arch -if supposed to be a *catenary arch* ! —that pit exhibits the ratio of the weight of the arch to the horizontal thrust of it . . .

Figure 1

Crucial information: I know the weight —I raised it by my own hands— so I know the horizontal thrust. A strange curve the Catenary: to assume that the shape of the hanging chain stems to its minimal potential energy state, defines that curve *completely*

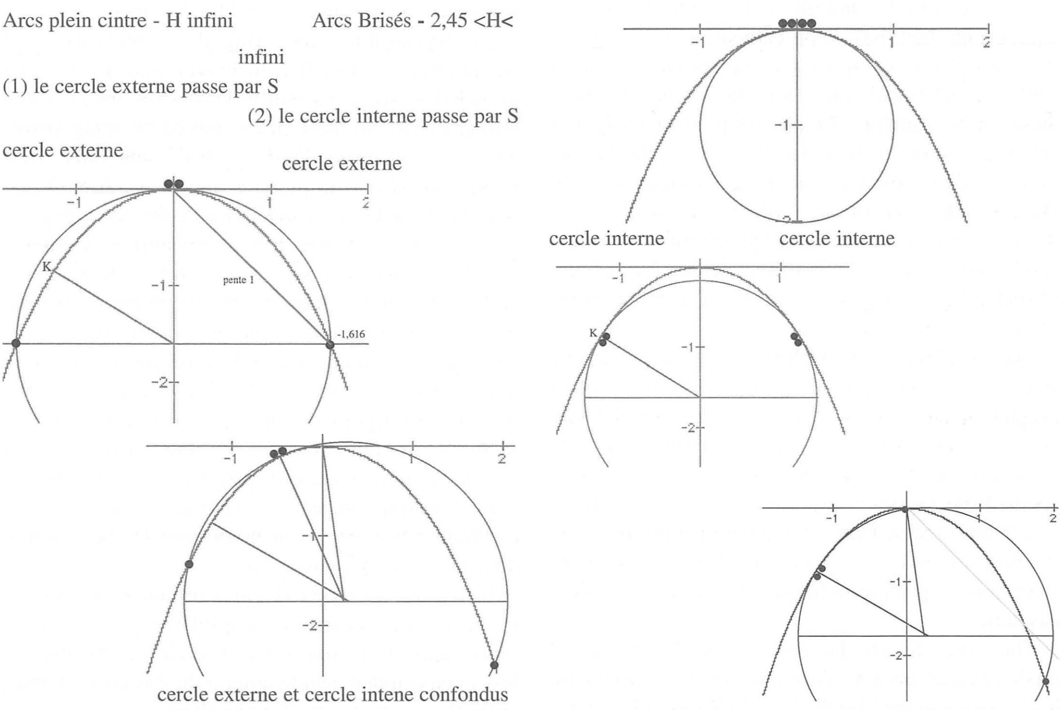
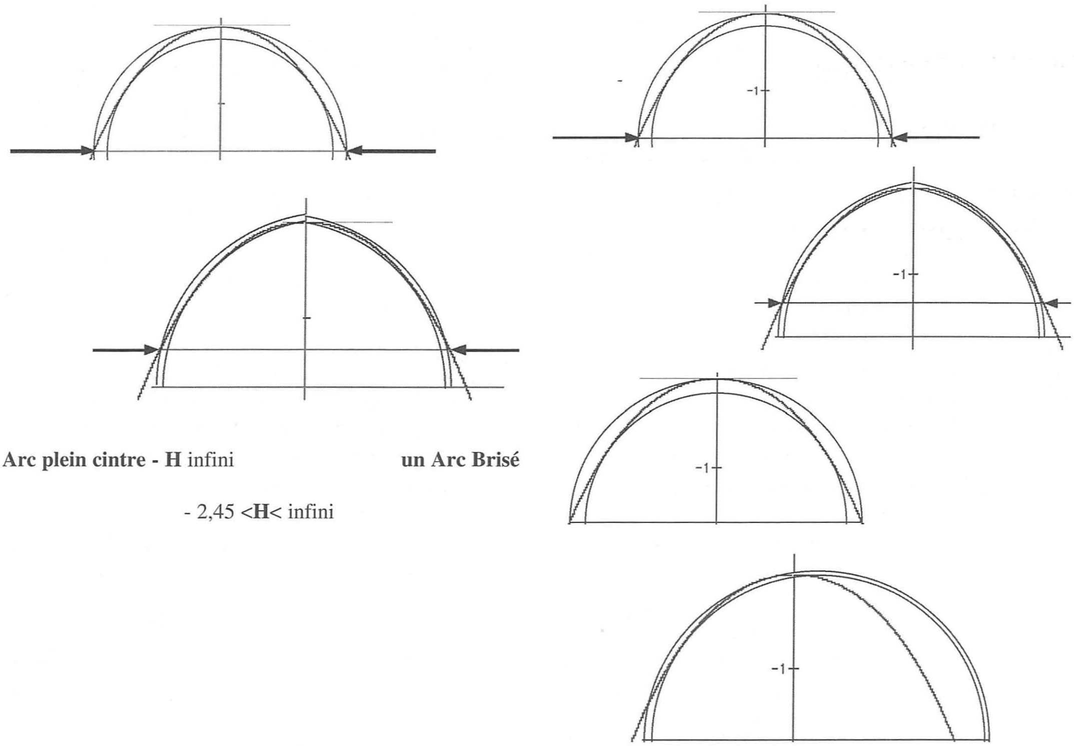


Figure 2

Distribution des points communs à une chaînette et à un cercle

(Fig. 1). A being of the mechanical world also belongs to the geometrical world. So appears an objective link of powerful meaning between Mechanics and Geometry. In fact, with all the precision we want, we can imitate that «optimal curve» by assembling a series of short circular arches of varied curvatures. The enlightened Builder will mime the Catenary with the gestures he knows and receipts given by the Geometer: by using circles drawn from different centers (Fig. 2).

First of all the Builder had to accept that the specific curvature marking the equilibrium of a hanging chain also marks the equilibrium of the heavy arch in tension between two fixed supporting points. He had to see that the envelope prepared by the stone cutter when enclosing a certain amount of matter inside a pair of circles, should host that *equilibrium curve* in a comfortable way. He had to understand that should that curve hardly escape an excessively thin enveloppe, the latter would dramatically fold at the spot of the undesirable excursion . . . and the arch collapse. To seize the tie linking an horizontal force and a vertical one by drawing an oblique line gives new power to geometric approaches. The Catenary works like a horizontal to vertical force converter (Fig. 3). With an obstination worth of compass's one when looking toward the North —rope and chain freely hanging show under which geometric necessities Nature grants them equilibrium. The mechanical algorithm provided by the mere handling of very common objects of the time (handling ropes in naval and military technologies for instance) can bring us to an efficient theoretical understanding level, by a rigorous although common reflection. Apprehending what such a logical tie means in terms of recognition of the laws of Nature, could possibly fit with what could run in European brains in the 13th, 12th or 11th



Arc plein cintre - H infini **un Arc Brisé**

- 2,45 <**H**< infini

Figure 3
Épaisseur de l'arc et niveau de Boutement

centuries. This gave birth to a vocabulary specific of the time's characteristic shapes: arches drawn on the basis of several centers, among which mainly, the *pointed arches.* So the specific quality of arches shaped in that way looks clear: it is, more than a supposed minor horizontal thrust, an *improved stability,* since —despite less material— the pointed shape prevents from the risk of flexion which is a deadly danger for arches.

The specific shape of any pointed arch can be specified in an objective way by a numeral index. For instance the term $\frac{1}{\cos\theta}$, where θ represents the angle of the radius reaching the key of the arch related to the horizon. Since we can find sketches of this in some pages of the famous Villard de Honnecourt Album, and as an homage to him, we suggest to indicate it by the letter **H**. We can also use the angle θ itself, or the position of the centers of the circles on the diameter of the pointed arch. It was refered, in didactic transmissions, to various famillies corresponding to steps regularly inscribed along those scales. For instance the so-called «arc en tiers point», although the exact meaning of that term is now being discussed. Every structural functions required determined shapes, so in a given monument —depending on its own cultural context— we find a specific range of arches shapes (Fig. 4).

How about a yet-to-be-invented theory for big masonry structures, which would lay the *rigourousness of a geometric determination* as a master principle ? It seems that a pragmatic reflection, chewed over and over and carefully tested —far from any kind of calculation in the sense we give to the word today— indicated the way: handling ropes in front of circles drawn on the surface of a testing wall, conveys the same indications as the graphic calculations of experiments led on the computer (i. e.: arch's thickness, level for abutments . . .) (Fig. 5). Most probably that theory had been first developed in the East, where, long ago —before the year One Thousand AD— and for specific reasons, most arches differed from the mere circle (Byzantium, Sassanid Empire, Ægypt). Architectures grew from such shapes, which could not let unaware European travellers eager to foster their own skills and performances at the dawn of a new rationalist age.

Should such an interpretation be accepted, we should also consider that an audacious challenge —the invention of the cathedrals— has possibly been achieved without using anything similar to the analytical algorithms which flourished with a growing refinement in the writings of Galilée, Descartes, Newton, Leibniz, Lagrange, Mach, etc. Success may have been the result of a skilled use of Geometry, and if we do not find explicitly related clues and demonstrations in ancient litterature —or if we are not prepared to read them— such a knowledge is peremptorily exhibited in the cathedrals themselves: aerial pavings forming shells 25 or 30 cm thick over 12 meter span —23 meters at Gerona— inscribe these science and understanding in space and time.

«Ronds Points» Sanctuaries in Circle: the Age of anthropic Centrality

A particuliar «locus» in the large cathedral church in the making was the Sanctuary, an object of distant contemplation for the people, an area accessible to the actors of the cult only. It is the place for the closest approach to the sacred species: i.e. for eucharisty and relics. The sanctuary is a safe room dedicated to fervour and contemplation, the focus of a grandiose staging proper to capturing the attention of crowds. A place where a sensitive and rigourous achievement in geometry had to be elaborated.

In a great number of churches it is by no way possible to walk around the sanctuary. It is so, at a small scale, in most of the monastic cistercian churches, and at a greater scale in carolingian cathedrals and also in a monument such as the Spire cathedral. Similarly at the hugest possible dimension in Haggia Sophia, the sanctuary backs a wall pierced with flows of light, contrasting with the luxurious galleries overhanging the central room. (Fig. 6 a, b, c, d)

On the contrary, at the beginning of the 12th century in the Loire Valley, a couple of monastic churches appear strongly articulated in an externally massive and internally hollow pyramidal shape. The design here is completely different. The idea of winding in concentric rings around the focal point, a row of huge pillars, and a deambulatory gallery, and a series of secondary sanctuaries —the apsidal chapels, looking like epicycles . . . — will be brought to emphasis up to become the specific mark of French architecture in the 12th and 13th centuries. This had been introduced

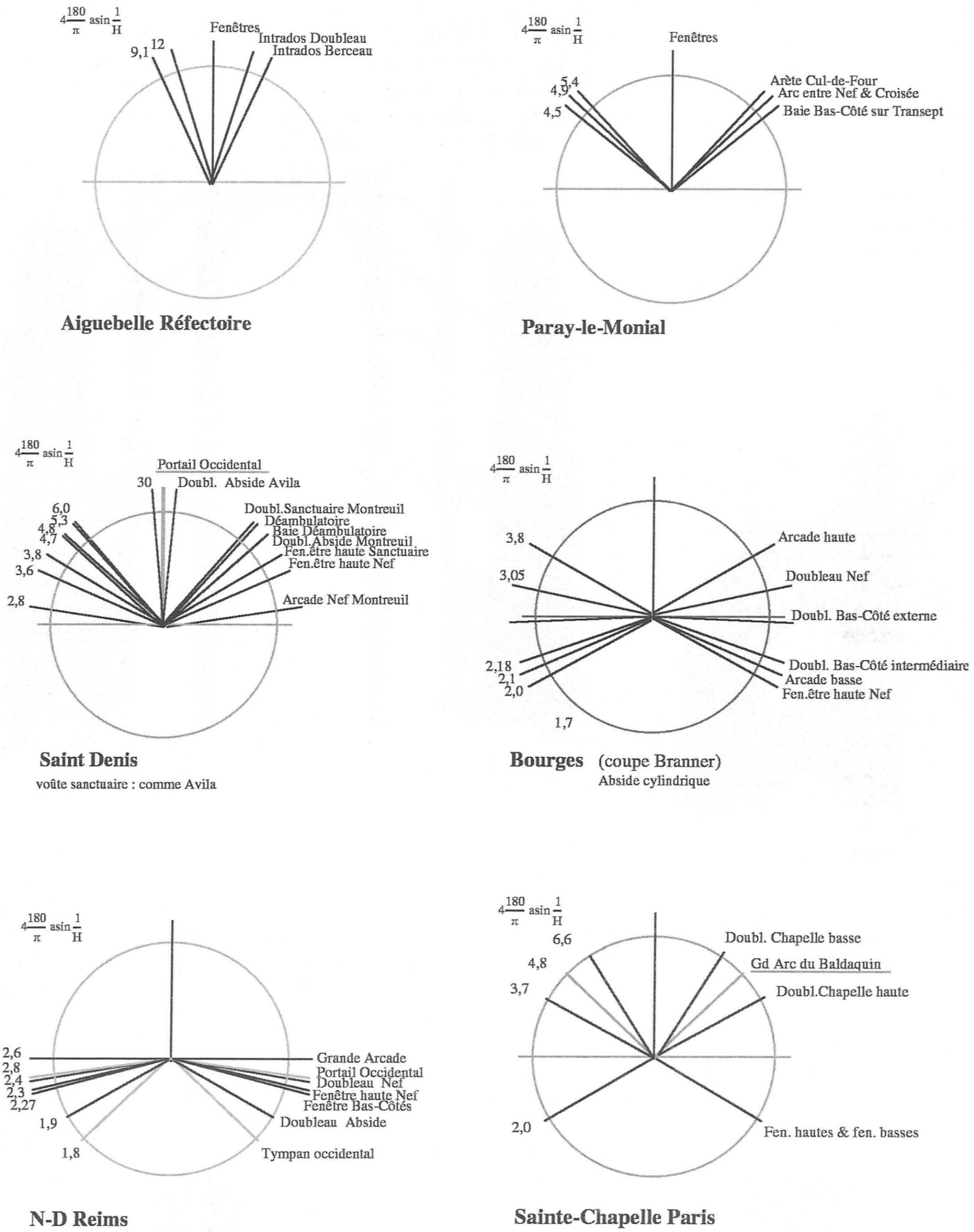
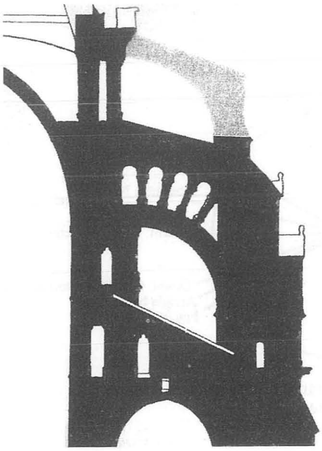
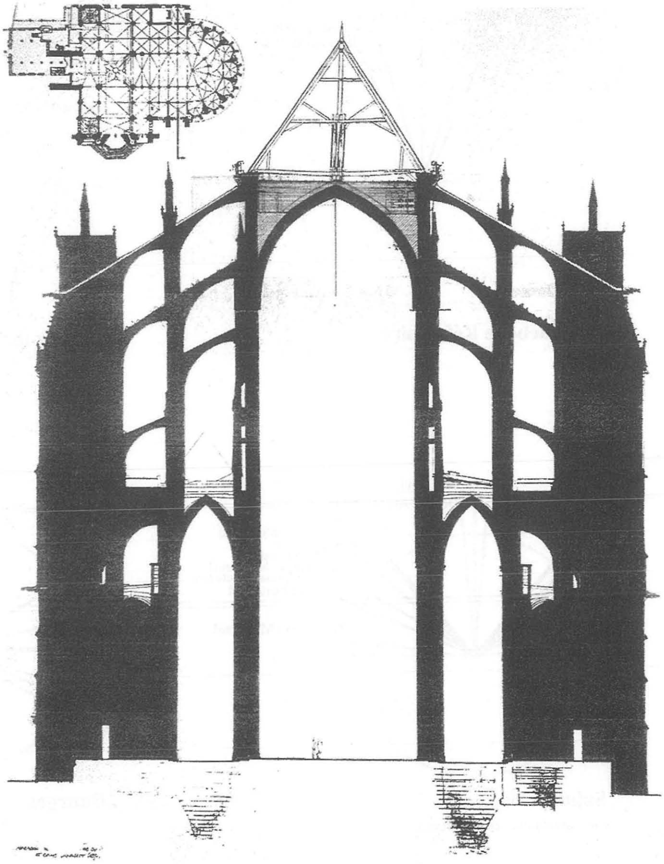


Figure 4
Arcogrammes



Chartres



Beauvais

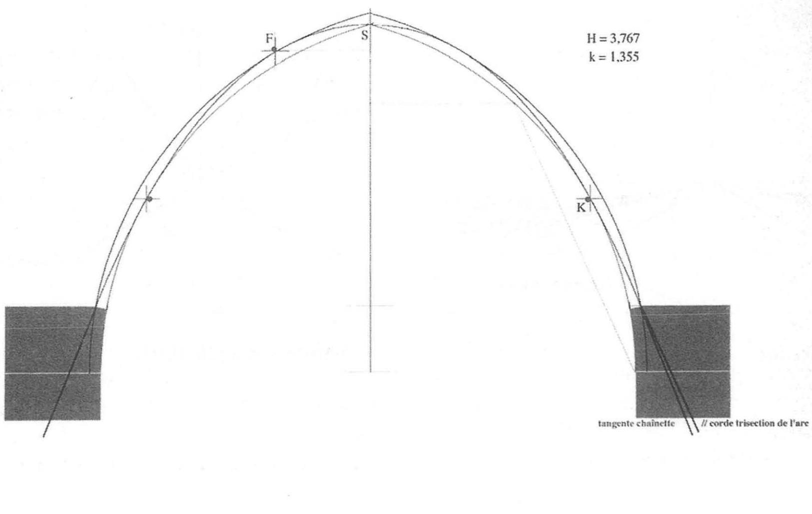
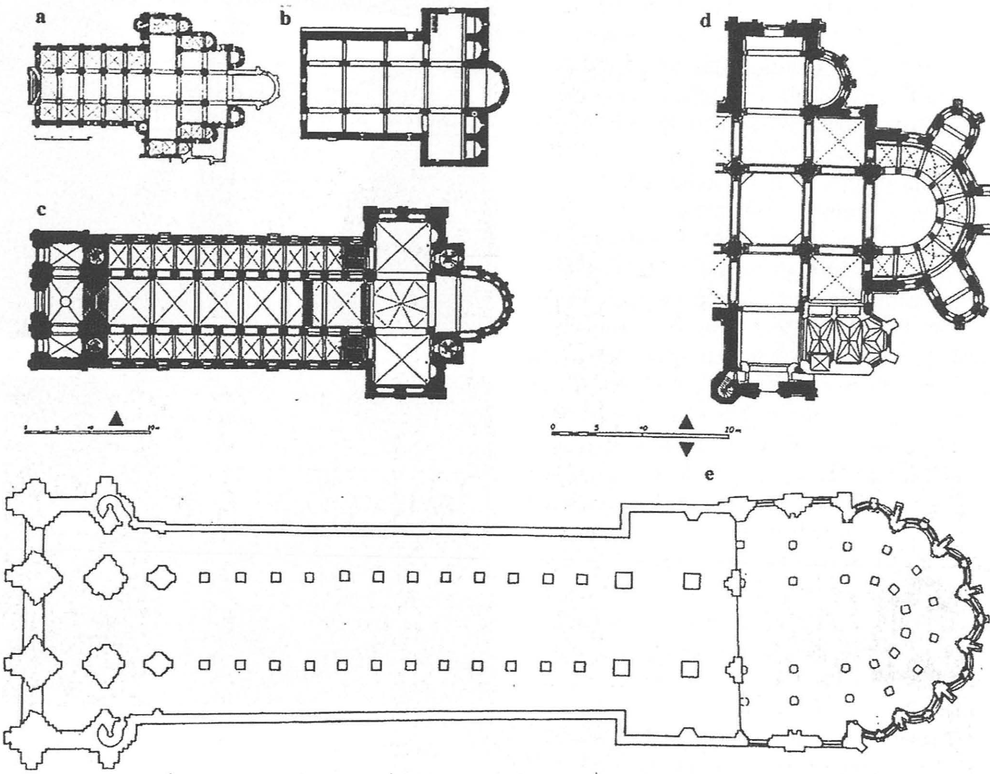


Figure 5



Figures 6 and 7

and stimulated as pilgrimages to relics increased at the end of the 11th century. The case of the crypta at the cathedral of Clermont-Ferrand is given as an early model (Fig. 7). The generating paradigma consists in a large circle drawn upon the ground, and evenly divided according to precise intentions —structural commitments and symbolic assumptions— as an echo to the Rotunda of the Holly Sepulchre in Jerusalem. The outcoming dial is often structured according to an even division of the circumference —like islamic astronomical devices were. The classic sign of solemnity in the Antiquity —the dramatic shell of the apses— is amplified by echoing rings in peripherical spaces. At the very focus is the front of the altar: the immaterial vertical axis is indirectly but strongly emphasized, as an exaltation of the concept of centrality which will later be outdated by Nicolas de Cues, Copernic and Giordanno Bruno.

All the necessary means, materials and tools were then set to work for promoting a prolific architecture of a kind never seen before. These were: stone and/or terra cotta, wood, iron, lead; the mental ability to decompose a large and complex concept and to extract from it accurately defined geometric components for recomposing the whole; teams of craftsmen producing in a fast and precise way thousand of pieces highly different from one another; perfectly operating transport and lifting devices produced by a technology acquired in military experiments; the activity of small groups of men trained in conceiving and prescribing the huge and unprecedented machinery, as a whole as well as in details; the will of wealthy and mighty lords having an eager desire for these works. This was the time when, in terms of structure design, the

Carpenter's strictly linear writing will combine

Beschreibung Aller Kirchen-Gebäude Der Stadt DANTZIG/

Worinnen Einer jeden Kirchen Grund-Riß/ Auffzug oder Abriß vollkömlich zu ersehen wie dann auch von den Kunstreichen Gewölbern in denen Kirchen/ sowol im Grund-Risse als Auffstellung derselben deutlich gehandelt wird.

Nebst Der Beschreibung aller anderen Kirchen/ so ausserhalb Walles in den Vorstädten gelegen seyn/ nach ihrer Maaß.

Verfasset und gezeichnet/ durch Bartel Ranisch/ Bürgern und Mauer-Meistern in Dantzig.

DANTZIG/ Gedruckt durch E. Edl. Raths und Gymnasii Buchdruckern/ Johann-Zacharias Stollen/ Anno 1695.

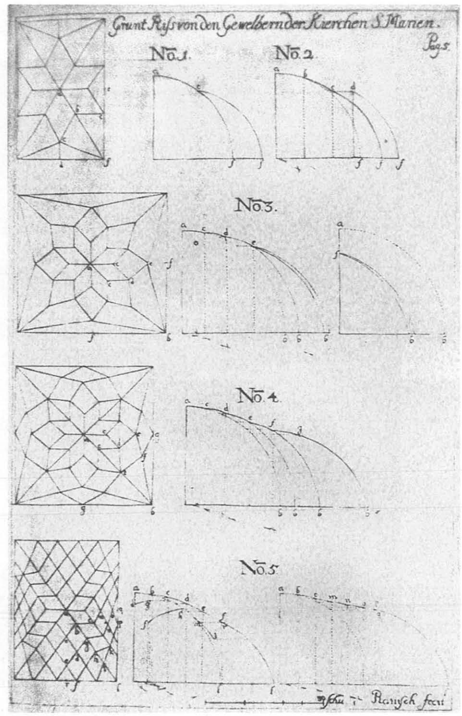


Figure 10
Bartel Kanish «*Beschreibung alles Kirchen Gebaude der Stadt Dantzig*» 1695

conditions of stable shape, the noblest among the Architect-Geometer's duties, (2) to design the sacred area as a spiritual astrolab, (3) to combine easy and efficient processes for translating the mental scheme into a real scale on the ground.

The first challenges being solved and a culture of mechanic-geometry having been built, the organizing inclination of the Geometer was then called by a number of topics: the field of carving and pictural composition, constituted by an unnumered amount of details up to the miniature architecture in the architecture. Some approaches served mnemonic more than heuristic purposes, such as conserved didactic writings concerning pinnacle's design or net vaulting's pattern (Fig. 10) . . . The law of necessity is not as strong then. Fancy wanders freely. No doubt that professionalism and expert's proudness rapidly produced enclosed, jealously protected islands of knowledge. No doubt that in such an environment —alongside the «Art du Traict» itself— legends flourished about supposed aesoteric items of knowledge, letting essentials fall into oblivion. Without a clear option for reasonable things, we can endlessly search for supposed theoretical drawings in architectures, and probably imagine rather idle chimaeras compared with the major commitments recorded above.

Does a consciousness of Geometry preceed the need for Geometry ? Or inversely ? There was a Geometry for agricultural people, one for Megaliths, one for Roofs, for Chariots, for Ships, a Geometry for Arches and Vaults Designers, there were Newton's and Leibniz' Geometry of curves and trajectories. Einsteinian Chrono-Geometry of cosmic spaces is not very familiar yet. Now we keep to the Geometry of Monge, Laplace and Eiffel, suitable to industrial forecasting.

We should not forget that in Europe, a thousand years ago, a Geometry and its Geometer appeared, necessary for inventing Cathedrals.

Historical investigation on the use of masonry pointing in Italy

C. Tedeschi
G. Cardani

Pointing is a finishing used in facing masonry walls with the aim of avoiding rain penetration into masonry from mortar joints; this is one of the principal causes of the different surface decays.

This study of the different pointing methods applied during the historic periods in Italy was strictly connected to an investigation on the mortar jointing (or repointing). Changes occurred during the centuries of the pointing technologies can only be understood after a historic research and a specific investigation on the different compositions of the mortar mixture used for pointing of the facing masonry walls.

The historical and experimental research on pointing was carried out within a EC contract and had the following aims: 1. to establish the historical periods when pointing was used in Italy; 2. to detect the pointing typologies recognising the historical period when they were proposed for the first time; 3. to collect information on mortars, on their execution techniques and on the used tools.

The paper will stress the importance of the historical research when dealing with a correct conservation of facing walls of historic buildings.

Introduction

The definition of pointing here reported was decided within the EC contract (Naldini et al. 2001a). Pointing is a finishing used in facing masonry walls with the aim of avoiding rain penetration throhgh mortar joints, one of the principal causes of the different surface decays.

Pointing consists in filling the bedding mortar joints, left recessed to a variable depth. Often the regularity of masonry facades is improved with different tooling methods, that can be performed compressing the pointed mortar joints and realising peculiar esthetical effects.

The study of the different pointing methods applied during the historic periods in Italy was strictly connected to an investigation on the choice of the best mortar for repointing.

The historical research was carried out in order to explain the differences in composition and tooling found during the on site investigation included in the contract. The study of the different historic mortars used for pointing in Italy is of great interest and useful in order to understand its evolution and changes along the centuries.

The first information on pointing comes from the Roman period and its use continued in different historical period till nowadays. This technique was alternative and/or contemporaneous to other finishing techniques which had the aim of protecting masonry and giving it an elegant aspect.

The historical and experimental research on pointing was carried out in a EC contract and had the following aims:

1. to establish the historical periods when pointing was used in Italy;

2. to detect the pointing typologies recognising the historical period when they were proposed for the first time;
3. to collect information on mortars, on their execution techniques and on the used tools.

One of the most difficult tasks during the EC research was to connect the Italian terms and names defining the different types of pointing, to the English one. It should also be noted that these terms can be different in different Italian Region. What in Italy now is called «stilatura» for pointing, in the literature can be defined whit different names such as, «lisciatura», «allisciatura», «stuccatura», «profilatura» and other as reported in Table 1.

In the following a brief history of *pointing* is reported, showing the most important applications of this technique along the centuries.

The technique was not applied with continuity; in fact there were periods during which alternative techniques such as joint smoothing were used.

The historical analysis shows how pointing and its execution on a facing wall are influenced by different factors:

1. the historical period in which pointing was realised;
2. the particular geographical area;
3. the material used (stones or bricks);
4. the workmanship ability;

	Other Italian Terms	**Period in Use**
«Stilatura» (Pointing)	*stuccatura*	1784-1999
	lisciatura	1957-1996
	rigiuntaggio-rigiuntatura-giunto rigiuntato	1982-1996
	allisciatura	1971-1996
	rabboccatura	1840-1986
	profilatura	1853-1974
	Intonaco-intonacare	1885-1928
	sigillatura	1925-1994
	rinzeppatura	Since 1840
	speratura	Since 1874
	raffilare	Since 1925
	rasatura	Since 1982
	giunto rifinito	Since 1982
	imboccare	Since 1633
	fugatura	Since 1987
	ripasso	Since 1996
	giunto rebocato	Since 1521
	giunto trullisato	Since 1521
	giunto smaltato	Since 1521
	giunto rebuffato	Since 1521
	giunto infrescato	Since 1521

Table 1
Different italian terms used for «stilatura» (pointing)

5. the economical factor;
6. the importance of the building;
7. the cases when a rendering of the masonry surface was applied over surface.

The paper will stress the importance of the historical research when dealing with a correct conservation of facing walls of historic buildings (Naldini et al. 2001b). A brief history of the pointing is then presented which does not intend to be totally exhaustive.

Types of pointing in the history

The types of pointing historically known are presented in the following table 2 and the first five are the most popular. In the table 2 the Italian definition is reported in brackets together with the English one.

Each of them corresponds to a certain historic period; none of them is older than the time of the Roman Empire.

All the types of pointing mentioned above developed during the Roman times, except for *v-shape* pointing, which was introduced and developed between the 16th and 17th cent. This shows on one hand the important role of the Roman period and on the other hand how our technical culture is still hardly connected to that great civilization.

The *cut to shape* pointing seems to be used only in the Roman time, while other types of pointing were applied also in the successive historical periods. In particular, *concave* pointing seems to be the most used in the history, till the 17th century, while the *weather struck* 3) pointing was more used in the Middle Ages. In the Byzantine times both the *weather struck* 2) pointing and the *flush* pointing were frequently used. The latter was used till the 16th and the 17th cent. (Vananzi 1971; Marta 1986; Carbonara 1996).

After the Middle Age the pointing technique was still used, even if it was less accurate and precise. Nevertheless reference is lost on the use of specific types of pointing (concave rather than weather struck, cut to shape, etc.). For this reason it seems more sensible to talk about the history of pointing from the point of view of the historical periods rather than from the types of pointing.

Roman times

To the Roman times belongs the first information on the use of the pointing in Italy. From that times through various developments pointing has arrived to the present times (Lugli 1957).

The Romans largely used pointing as a protection of joints for facing walls. Nevertheless most of the walls that now appear as facing walls were actually rendered in the Roman times. In these cases the very accurate technique of pointing, which required skilled masons, was not applied. On the contrary, tooling was often applied on mortar joints before rendering; therefore this technique was also used to reproduce the rough surface necessary for an easy application of renders, in addition to esthetical reasons.

Usually only small and simple buildings which could not be rendered for economical reasons had facing walls with pointing of mortar joints. For this reason pointing was diffusely applied to funerary monuments; nevertheless rare examples of pointing of important walls were also found (Lugli 1957)

Pointing was applied to the entire masonry surface and concerned buildings made with bricks or «tufelli», small tuff elements. For facing walls, special bricks were used, thinner then usual, wedge-shaped to give better adhesion to the internal leaf and to show externally mortar joints as thin as possible. In order to increase the homogeneous aspect of the façade pointing was carried out, giving a very smoothed surface (Figure 1), (Marta 1986; Carbonara 1996).

The fundamental aim of pointing was to obtain a very smooth surface by tooling the mortar joint with a trowel, so that all the roughness and the voids could be eliminated; the joint became perfectly smooth and aligned with the brick or stone courses («flush» pointing). The difference between the joints and the masonry elements was only declared by the different colour. In some cases also the colour tended to be similar, particularly when the pointing was done mixing with the lime a certain quantity of brick powder («cocciopesto»). The wall surface, in this case, assumed a chromatic uniformity obtained on purpose.

Pointing also was a way for compacting and filling completely the joints, so that a better protection to the masonry against aggressive environment was given. In order to realize this type of finishing very skilled masons were needed (Adam 1988).

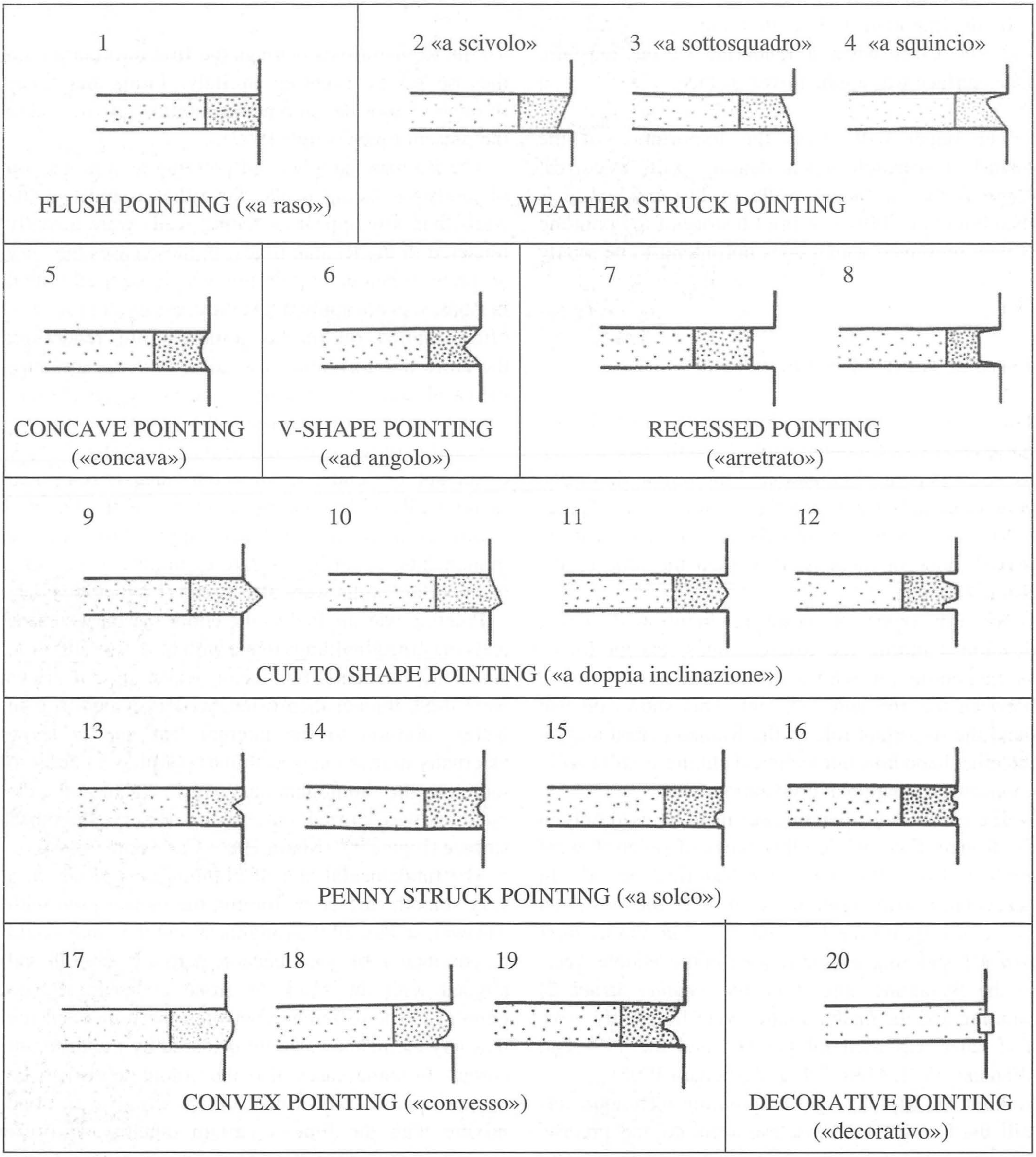


Table 2
Types of pointing historically known in Italy

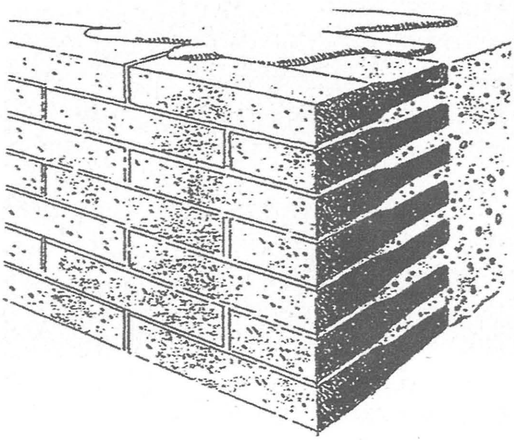
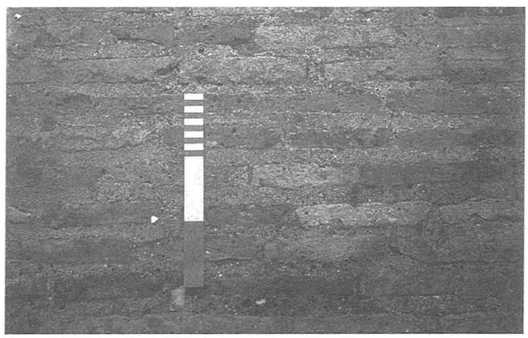


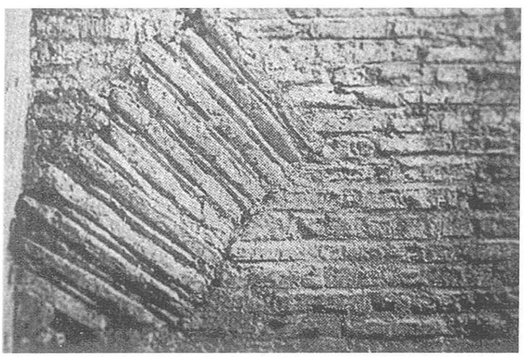
Figure 1
Wedge-shaped bricks to show very thin joints on the external side and to give a consistent thickness of the mortar on the internal side.(G. Carbonara 1996)

The «concave» pointing appeared only in the 3rd cent. A.D. during the period of Antonio Severo and Aureliano (235–270 A.D.) and became very popular under Massenzio and Costantino (306–337 A.D.). It was dropped at the end of the 4tht cent A.D. and substituted by re-pointing; then it appeared again in the 6tht cent and applications can be found also in the 7tht cent. It was not realized with the blade but with the round part of the trowel, so the joint assumed the typical concave configuration (Figures 3 and 4).

Concave pointing was often used (during the Roman Empire and also later on), together with or alternatively to the «tooling». This finishing technique is sometimes considered the opposite of the «pointing» because it does not need to add new mortar; on the contrary, it requires a removal of mortar from the joints with the trowel or other tools and in the meantime a mortar compaction (Lugli 1957).

The Romans also used other types of pointing, largely diffused, in addition to the flush pointing, each of them belonging to a particular historic period. F.i. pointing «weather struck 2)» was diffused since the cent A.D. during the Imperial time and after it was used up to the 14–15tht cent A.D. Its maximum application took place during the Paleochristian period. *«Cut to shape»* pointing was used since the 1st cent A.D. in thick joints. Its use continued until the 4–5tht cent A.D. (Figure 2).





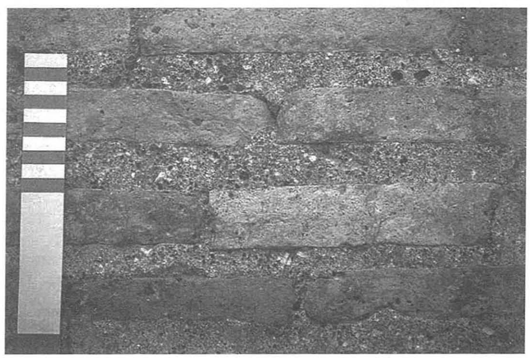


Figure 2
San Giovanni in Laterano: example of curtain wall with «cut to shape» pointing of joints. (R. Marta 1986)

Figure 3a, b
Basilica of Massenzio: example of curtain wall with concave joints

Figure 4
S. Stefano Rotondo: example of curtain wall with concave joints

Figure 5
Terme di Diocleziano: example of roman

Tooling was performed to have smooth regular curtain walls. It developed in the Roman times and was used until the12th century. Then it appeared again in the second half of the 16th century, above all in poor and not very valuable masonry. Since the Republican period of ancient Rome, the two techniques, pointing, and a tooling, above all the concave type, lived together or alternatively till the 12th and 13th century (Marta 1986; Marta 1989). The weather struck 2) pointing had a limited use in the Roman times and it never became popular afterwards.

The mortar used for pointing was applied in thin layers and composed by lime and sometimes very fine pozzolana sieved to the very fine size (perhaps to ensure the pozzolanic reaction) and fine sand. The binder quantity was much higher than the one used for bedding joints so that the mortar became a sort of glue (Lugli 1957)

In the following table the list of the most important examples of pointing found for the Roman times is given (Figures 5 and 6):

Palaeochristian times

The palaeochristian architecture became popular in Rome during the 4th and 5th centuries A.D., when the culture of construction was at the top of its technical capacities. Together with important buildings of civil roman architecture, the first Christian churches were in fact built such as the Basilica of Massenzio (306–312 A.D.), enlarged then by Constantine (312–337 A.D.) (Benevolo 1987). The palaeochristian building techniques were very similar to the Roman ones, from which both the building methodologies and techniques derived to better protect masonries from the atmospheric agents: one of them was pointing.

Two types of masonry structures were developed, from the Roman times:

- opus latericium, with only bricks binded with mortar;
- opus mixtum, with brick and stones (usually «tufelli») in alternate courses 31–36 cm high, with about 5 courses for each material.

The construction of this masonry was usually followed by pointing of mortar joints and then by

Figure 6
Mausoleo of S.Costanza-palaeochristian pointing

Buildings Name	Location	Date	Pointing Type
Diomede's House	Pompei		*Weather struck*
External wall of Lateranense Baptistery	Roma		*Cut to shape*
«Villa dei Misteri»	Pompei		*Cut to shape*
Northern aisle of San Giovanni in Laterano	Roma	313 - 337 A.D.	*Cut to shape*
West end and corner of the San Pietro in Vinculis façade	Roma	432 - 440 A.D.	*Cut to shape*
Gordiani's House	Roma	235 - 270 A.D.	*Concave*
Works of Sisto III SS. Giustino and Cipriano chapels in San Giovanni in Laterano Baptistery	Roma	432 - 440 A.D.	*Concave*
Terme deciane	Roma	235 - 270 A.D.	*Concave*
Terme di Diocleziano (Fig. 5)	Roma	284 - 305 A.D.	*Concave*
Giulia Basilica	Roma	284 - 305 A.D.	*Concave*
Spacus Aquae Marciae	Roma	284 - 305 A.D.	*Concave*
Massenzio Basilica	Roma	306 - 312 A.D.	*Concave*
Templum Divi Romuli	Roma	306 - 312 A.D.	*Concave*
Templum Veneris et Romae	Roma	306 - 312 A.D.	*Concave*
Costantino Basilica	Roma	312 - 337 A.D.	*Concave*
Santa Sabina (Fig. 4)	Roma	337 - 526 A.D.	*Concave*
SS. Giovanni e Paolo	Roma	sec. 5th A.D.	*Concave*
Harbour walls	Ostia	sec. 5th A.D.	*Concave*
Lateranense Baptistery	Roma	sec. 5th A.D.	*Concave*
Porch of «Dei Consenti» and hall of the Church of San Balbina	Roma	sec. 5th A.D.	*Concave*
Church of Santo Stefano Rotondo	Roma	sec. 5th A.D.	*Concave*

Table 3
Examples of pointing found in Roman Buildings

tooling, showing the upper edge of the bricks, in order to have a weather struck pointing 3) (Testini 1934).

The first example of this pointing in the palaeochristian architecture is the Mausoleo of S. Costanza in Rome, of the 330 A.D (Figure 6). As it can be noticed the joint was very thick reaching frequently the thickness the brick

The Byzantine times

The Byzantine architecture was characterized by innovation between the precepts of the Roman time and the reviews of the palaeochristian time.

The high skill of the Romans in the construction of masonry walls was put under discussion as the expansion of the Byzantine Empire started in the 4th cent. A.D. (Benevolo 1987). Even if the fundamental principles of the Roman wall construction technique were not refused, the Byzantine period gave a new great supremacy to the brick. The walls were not rendered anymore so that the beauty of the brick texture of the facing wall could be seen. In Italy the city of Ravenna, which became the Occidental center of the Byzantine technology, clearly shows this new taste.

Also Byzantines as the Roman built with a three-leafs masonry, but the internal leaf became less

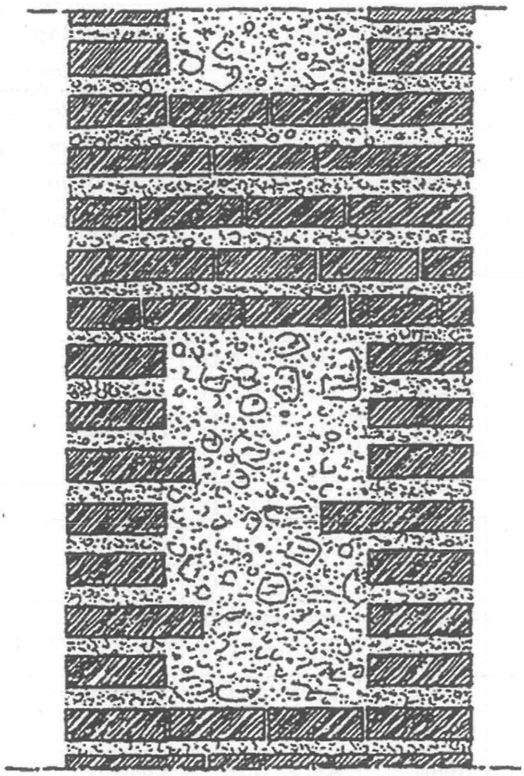


Figure 7
Prevailing masonry building technique in the Byzantine time (C. Latina. 1994)

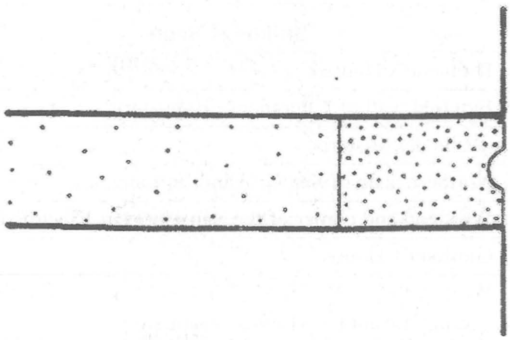


Figure 8
Typical penny struck pointing of the Byzantine buildings

homogeneous and solid while the external leaves became even more important not only under the aesthetic but also under the structural point of view. In fact, first the external leaves were built and only later the internal cavity was filled with crushed stone and mortar. Five rows of bricks were laid at regular range through the depth of the wall connecting the external leaves and reinforcing the structure (Figure 7; Mango 1978; Latina 1994). A new supremacy of the curtain wall started, showing the beautiful texture pattern of the facing bricks. These bricks had square shape with sides of 35–38 cm and a height of 4–6 cm. They were laid complete and not broken in diagonal as the Romans usually did (Latina 1994).

The mortar used for Byzantine masonries appears as a concrete, rich in sand, gravel and brick fragments also of large dimension. For that reason the mortar joints were finished by pointing with finer, more homogeneous and with a very high cohesion mortar. The pointing mortar was then compressed in the joints with a special beveled tool, which engraved a thin groove (Figure 8). Weather stuck (2) pointing was also used showing part of the edge of the lower brick (Zanini 1994). Another fundamental characteristic of the Byzantine buildings is the high thickness of the mortar joints, which increased in the centuries, passing from a joint/brick ratio of 1:1 in the 4th cent. A.D. to a 3:2 ratio or more two centuries later (Mango 1978; Latina 1994).

The pointing was in these cases connected to a special technique for facing masonry walls, which was called «recessed brick», consisting in brick toothed layers (Figure 9). Only later on, the most recessed bricks were hidden under a new mortar joint creating a peculiar flush pointing, which could also be underlined by horizontal tooling. The effect was that of thick mortar joints even thicker than the bricks, made regular by horizontal incisions. This technique in use since the 5–6th cent. continued to be used also later, since the Byzantine architecture used it until the 12th cent.

Also in this case the documents point at the use of a mortar for pointing which was finer and more homogeneous than the bedding mortar (Figures 9 and 10), (Mango 1978; Latina 1994).

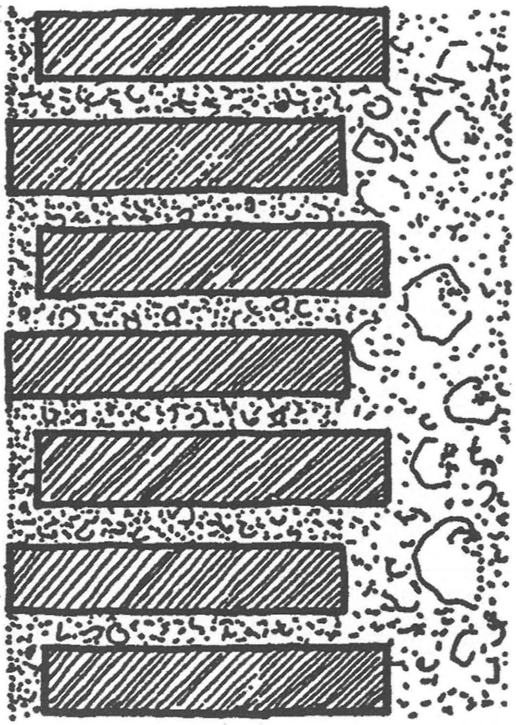


Figure 9
Curtain wall with recessed brick wall. (C. Latina 1994)

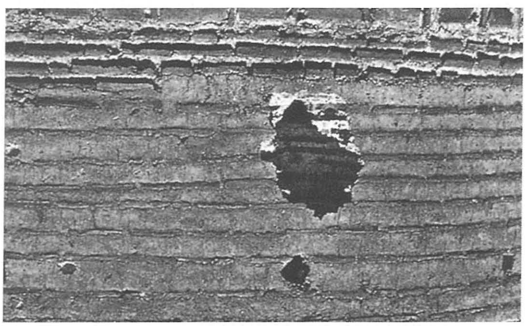


Figure 10
Nicea wall: example of curtain wall with recessed brick (11–12th cent.). (C. Mango. 1978)

From the Sixth-Seventh Centuries to 12th Cent

Starting from the 6–7th cent. until 1084, when Rome was invaded by the Normans, the masonry of the external surfaces loose the previous regularity, having irregular brick courses not respectful of horizontality and very thick mortar joints. The lack of good materials and skilled masons was the cause of the missing of good construction rules and of some finishing techniques as pointing (Marta 1989). Only in the 13th century there will be a new revival for pointing.

The Ages from the 13th cent. To the 14th cent

Pointing as a technique of surface finishing reappeared in 13th cent. The weather struck 3) pointing (Figure 4), seldom used in the Roman times, was very popular during the Middle Ages.

Other types of finishing were also used, as the «false curtain wall» which was called in Italy «muratura di tevolozza» (Figures 11 and 12). In this period this technique becomes more popular than other finishings, even more than pointing. In fact in the medieval times there was a reduction of the productive and technical capacities also due to the frequent reuse of materials removed from old constructions This explains the use of different and non-homogeneous elements in the same wall. Therefore the masonry was usually out of plumb and with irregular courses.

The false curtain wall was developed in this period: it is a peculiar executive technique which gives the idea of a regular and homogeneous wall, using a fine layer of limewash applied to the masonry and fairly hiding the single bricks. Afterwards, before the hardening of the mix, the joints were either horizontally or vertically tooled and, sometimes, without correspondence with the underneath joints (tooled false curtain wall). The tooled false curtain wall appeared during the second half of the 11th century and became popular in the 13th–14th century.

Sometimes a reddish colour was used to imitate bricks, while tooled joints were left white, simulating mortar joints (painted false curtain wall). The painted false curtain wall developed between the 12th century and the beginning of the 13th century, but also in the 15th century it had a considerable use. Usually it was

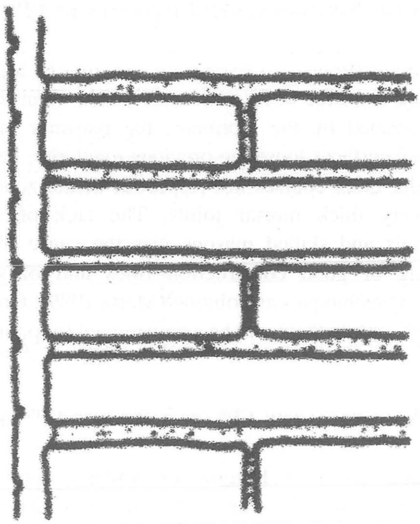



Figure 11a,b. a)
Scheme of false curtain wall (G. Carbonara 1996) and b) example of false curtain wall (E. Pallottino 1990)

not applied on the whole building, but only on the main parts (Carbonara 1996; Marta 1989).

Then, even if the rendering of the masonry «di tevolozza» was the quickest and most practical remedy to give the impression of good masonry work, also pointing was used. The use of tooling flush of the mortar joints with the trowel, in order to eliminate the overflowing of mortar from the brick or stone, could give the alignment and aesthetically the impression of a better work. The pointing was done with a fine and soft mix made with a mortar rich in finely sieved rich lime.

After the 13th century the «false curtain wall» substitutes the pointing remaining the most used technique of masonry finishing for the rest of the medieval times.

Anyway pointing continued to be applied on curtain walls, even though seldom. Its use, in that period, showed traces of the productive and economical events, as well as of the particular geographical area.

Examples can be given by Pisa and Southern Lazio.

Some careful studies showed that during the Middle Ages there were two different masonry typologies, which were often used in the urban buildings of Pisa, whose joints were pointed:

— the first one refers to the tower buildings, realised with re-used materials, essentially stone, laid in homogeneous and regular courses with pointing and tooling of thick mortar joints (half of the 11th century-beginning of the 12th century)
— the second typology is represented by buildings formed by two towers, joined by a covered passageway. In this case the courses are not always regular and the mortar joints are high, with pointing and sometimes also with tooling (first half of 13th century).

Referring to the South Lazio case, small blocks masonry, mainly tuff, was frequently used during the

Building name Location Date	Pointing Type		
Walls with small square tuff blocks	Palombara Sabina (Roma)	13th cent.	weather struck 3)
Right Tower of the San Cesareo façade at the «Terme di Caracalla»	Roma	13th cent.	weather struck 3)
«Fortezza dei Savelli» in Aventino	Roma	13th cent.	weather struck 3)

Table 4
Buildings with weather struck pointing in Middle Age

Figure 12
House in Piazza Cancelleria, Roma: example of false curtain wall (P.N. Pagliara)

13th century, until the beginning of the 14th century. These blocks were disposed in regular and perfectly horizontal courses, with pozzolanic mortar joints 1–2 cm thick, which sometimes had weather struck 3) pointing. The boundary walls of Torre Santi in the Latina valley are an example.

Table 4 reports a list of weather struck 3) pointing examples:

Sixteenth and Seventeenth century

Within the 16th century a new chapter on the techniques of construction of masonry walls is written. The brick facing walls are seriously re-proposed not only from the structural but also from the aesthetic point of view. The brick masonry was consistent, strong but what is most important, of great beauty and effect.

In the first half of the century the attention is devoted to bricks; their external face is submitted to polishing, sharpening and shearing processes. In the second half, the interest is given to the joint finishing. The joint was now part of a masonry made with poorer bricks but with joints completely filled also with the use of finer mortars and subsequently pointed. As already seen in the Mediaeval times, the pointing became the way for simulating verticality and smoothness in rough masonry.

In the 17th century both the bricks and the mortar joints were treated respectively with smoothing and pointing in order to reach a perfect monolithicity appearance of the masonry surface as reported on the contemporary contracts. The expression «sharpened, smoothed and joint marked walls («cortina rotata, stuccata e segnata») meant a wall built with sharpened bricks (on site or before the construction) and with joints tooled by pointing (Figures 13, 14 and 15). This particular technique was adopted in Rome and in the Lazio Region (Bertoldi et al. 1983)

The pointing was considered particularly important for its properties of covering bricks inhomogeneities and giving verticality to curtain walls. When pointing

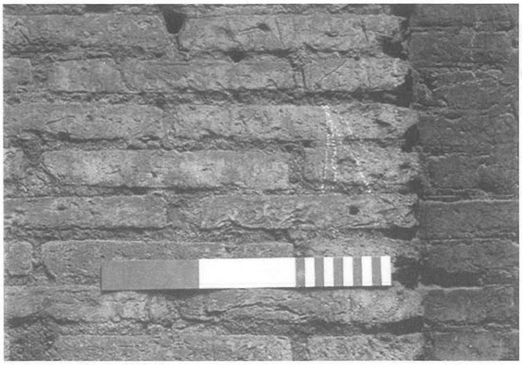


Figure 13
Sant'Andrea della Valle: example of filled and engraved curtain wall (17th cent.)

was applied to masonry of poor quality, the mortar joint was tooled in such a way to cover the brick edges, in order to protect them from the aggression of time and environment. Flush pointing was so obtained, but the outline could assume a concave configuration using a tool with a cylindrical shape. In the lining walls built in a masterly fashion, pointing was made in the middle of the joint, using a tool which left a not very deep semi-circular sign, whose diameter was about 4 mm. A tool with a triangular section, which cut deeper into the mortar, was used but not very frequently (V-shape pointing).

The mortar for pointing was different from the bedding mortar; this last in fact was easily crumbling and with large grain size. The pointing mortar was usually finer, compact and then strong; it was obtained by mixing pozzolana finely ground with a selected lime. Useful information can be deduced from the contracts with the producers; they always mention a good quality lime without clots or powder and well fired. Special recommendations were also made concerning the necessity of a long time of accurate slacking in order to avoid the formation of CaO lump once the pointing was carried out. Together with the lime, the pozzolana is always mentioned, while the sand is never recommended as a necessary aggregate. The pozzolana should be of good quality with high hydraulicity and without bad inclusions of clay or soil (Bertoldi et al. 1983)

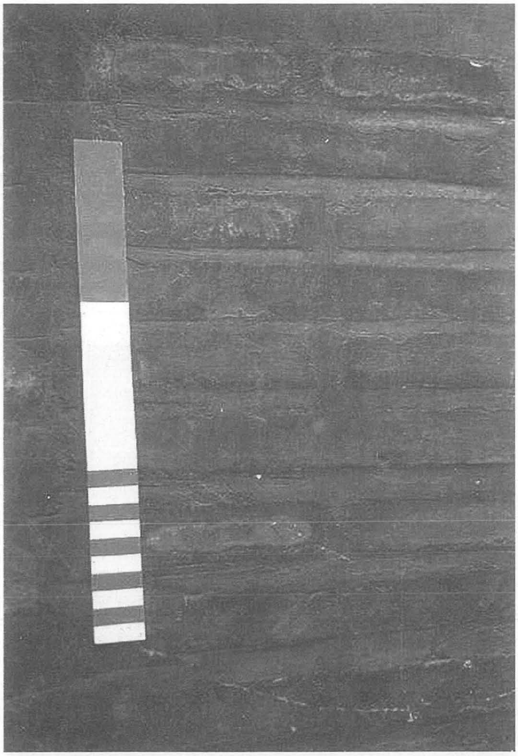


Figure 14a,b
Palazzo Mattei, Rome: example of weather struck (3) pointing (17th cent.)

The Eighteenth and Nineteenth centuries

Information about the use of pointing in the 18th century never appeared in the texts, except for the

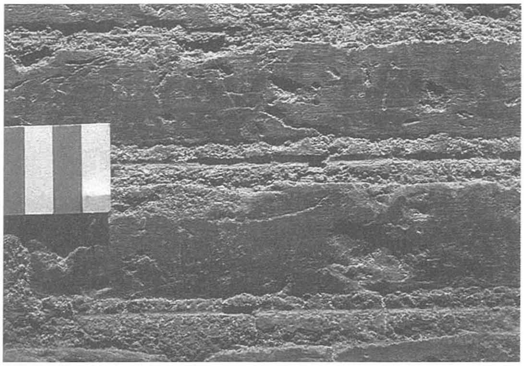


Figure 15
Palazzo Mattei, Rome: example of tooled pointing (17th cent.)

mention made by Francesco Milizia in his «Principi di architettura civile» (1781). According to Milizia the pointing should be carried out in case of facing masonries in which the bricks were sharpened only on their facing surface (half or false curtain work); in that case a very small fine size mortar should be used made with lime and brick powder and subsequently pointed (Milizia 1972).

A large use of pointing was made in the 19th century when specific manuals were produced. In the manuals very accurate descriptions concerning especially the pointing mortar composition can be found. The mortar had to be finely graded and as dense as a stucco or a glue. It should be made with lime and very fine ground sand or brick powder. Other materials could be added as marble powder or ground furnace blast cinders from the steel production (Cantalupi 1874).

Lime-gypsum mixes, already diffused in the 17th and 18th cent., in the Regions were gypsum could be easily found, as Emilia-Romagna, were frequently used. Pointing and re-pointing were also made with pure gypsum (Chiari et al. 1992)

The choice of the mortar composition was strongly dependent on the type of masonry: e.g. for a stone masonry surface a very carefully prepared hydraulic lime was preferred while, in the case of brick masonry, hydrated lime and brick powder were suggested, obtaining also in this case an hydraulic mortar (Breymann et at. 1885).

In the 19th century the use of cement started; the very first recommendations for the use of a cement based mortar for pointing can be found in the manuals or in the contract briefs. It was especially suggested to use painting after the joints were filled in order to make the operation less invasive from an aesthetic point of view. The colors had to be chosen in order to underline the texture of the masonry (Latina 1994)

The twentieth century

The 19th century brings the richest evidence of the use of pointing, which is described in the manuals as a technique for refining the joints and protecting the masonry. Several manuals also report a detailed description of the mortar types to be used. The cement based mortars were preferred as they were already used at the end of the previous century and totally substituting the lime mortars. Only some mention is made of the lime based mortars during the first two decades of the century; an hydraulic high fluid lime mixed with pigments in order to reduce the difference in color between the pointing and the bricks is suggested. Therefore it is possible to find suggestions of mixing lime with different colored materials as brick powder, colored ashes, iron oxides and even soot.

Usually starting from the third decade of the century only the use of enriched cementious mortars composed by cement and fine sand is suggested. The two components should be mixed dry and sieved before adding the water. Furthermore colored cements and sands with different tonalities are suggested, different from the bedding mortar materials and used in order to give a special appearance of brightness and colorfulness (Smith 1974).

Only in the nineties the idea of using mortars similar to the bedding mortar is stressed out being the pointing mortar richer and with finer grain size distribution (Tubi 1993). The pointing mortar has to be compatible with the bedding one and also attention is paid to the esthetical aspect.

The mortar can be white and clearly mark its difference from bricks or be mixed with colored pigments or brick powder in order to give more uniformity with bricks (Menicali 1992).

In the last decades also the possible mechanical role of pointing as joint reinforcement is supported to

give more strength to the masonry in seismic areas (Latina 1994; Baronio et al 2001).

Conclusion

An overview of the history of pointing in Italy was presented as a background for the evaluation and planning interventions.

Pointing plays not only a technical role, as a protection of masonry, but also an aesthetical role and contributes to the definition of the façade aspect, varying in the course of time. It is strongly dependent on the building techniques used, the available materials, the workmanship ability and the importance of the building.

The aesthetical role of pointing and tooling of mortar joints reflects the current building techniques of its time; therefore the original surface material should be preserved if not damaged due to deterioration processes.

Restoration works should guarantee the chemical-physical and mechanical compatibility from a technical point of view but also a compatibility from an aesthetical and historical point of view with the original support. It should be noticed that unfortunately important roman monuments changed the aspect of their façades as a result of radical restorations, loosing the original surface and thus the original document. After a recently photographic survey, a lack of respect of the historical materials and of the techniques used in the past appeared evident. This aspect will be studied in a further research in order to choose appropriate mortars for re-pointing.

Acknowledgments

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Building the cathedral of Noto

Stephen Tobriner

The Cathedral of Noto still dominates its city with grace and majesty despite its gutted interior and broken dome. The collapse of S. Nicolò on 13 March 1996 was just the latest misfortune in a long succession.[1] From shortly after the inception of the city of Noto on its present site in 1693 until the late 20th century collapses and closures caused by earthquakes plagued the church. The foundations of the original Chiesa Madre of S. Nicolò can be still be seen seven kilometers northwest of the present city among the ruins of old Noto (Noto Antica), destroyed in the earthquake of 1693. The Baroque city of Noto and its Chiesa Madre of S. Nicolò are products of a massive earthquake reconstruction effort which continued into the late 18th century. When earthquakes rumbled through the new city of Noto in 1727, 1780, 1818 and 1848 each damaged or collapsed S. Nicolò. The last earthquake to strike the city in 1990 opened cracks in the church which directly contributed to its failure in the rainstorm of 1996 (Gavarini 2000).

Figure 1
S. Nicolò. Façade overlooking the main piazza of Noto with a fragment of the dome still standing in 1998 (photo: author)

Since S. Nicolò experienced multiple earthquakes it is fair to ask whether the architects and stonemasons chosen to build or repair it attempted to make the church seismically resistant. Only construction documents corroborated by the ruins of the building itself can definitively answer this question. The challenge is to try to understand the architect's or builder's intention. The methods 18th-century Sicilians used to insure stability in earthquakes might differ markedly from our own. For example, one commonly held principle of antiseismic design derived from Classical authors and advised by architectural theorists like Antonio Averlino (Il Filarete), Andrea Palladio, and Francesco Milizia (Laner and Barbisan 1986, 13–27, 30–35, 56) was that buildings should be constructed over caverns or incorporate vertical shafts and hollow walls to avoid inhibiting vapors expelled from the earth during an earthquake (Guidoboni 1989). This idea is so counterintuitive we might miss it even if we saw a building intentionally built over a void. Other intuitive ideas about how to stabilize a building are closer to our own. The Mannerist architect, Pirro Ligorio, after examining the ruins of Ferrara after the

earthquake of 1570, offered his own observations about building safety (Guidoboni 1997). He criticized buildings that were simply too old, built with thin walls, lacking in reinforcement, bonded with inferior mortar. He blamed the craftsman guilds working without the guidance of a trained architect (like himself, of course) for the poor design and execution of the buildings that failed. His remedy was first to build well, with the best of materials and to use iron ties where necessary to bond walls together. He saw evidence of heavy exterior walls oscillating at different frequencies and striking one another. He suggested heavier than usual internal partitions to help stabilize these walls. He proposed uniform wall thickness as a way of insuring that buildings moved together in earthquakes and hypothesized that regular ground plans were far more resistant to shaking than irregular ones. Ligorio's intuitive reasoning seems considered, and generally in accord with present-day ideas of seismically resistant design. He, and countless architects who followed him, had to face the problematic behavior of brittle masonry walls which lack resilience when subjected to lateral forces generated by earthquakes.

The temporary church of S. Nicolò built in 1693 was certainly influenced by the fear of earthquakes. Because citizens feared the return of the deadly earthquakes which leveled not only Noto, but more than forty cities in Southeastern Sicily, they built small low structures throughout the 1690s (Tobriner 1982). The *baracca* of S. Nicolò, like others in the city, was modest. But within a decade, all over Noto, the temporary buildings were being replaced by larger ones in stone. Among these permanent building was S. Nicolò, begun in 1696. Like other buildings in the new Noto, S. Nicolò, was a patchwork of newly quarried and previously cut stonework. As stonemasons established quarries on the slopes of the new site of Noto, they sent mule train after mule train to Noto Antica to excavate stone from the ruins. The marble portal of the main doorway of S. Nicolò, lying in ruins in Noto Antica, was transported to the new city in 1696 and incorporated in the new façade. In 1718 the insignia of the city found in Noto Antica was solemnly affixed to the façade of the new Chiesa Madre clearly underscoring the transfer of the city.

In the midst of reconstruction a major earthquake struck Noto in 1727, badly damaging the new stone S. Nicolò for the first time (Boschi et al.1993). So badly damaged was the marble main portal in the earthquake of 1727 that it was at risk of total ruin. This decorative feature and the stone around it which had previously collapsed with the old church in 1693, nearly failed after it was installed in the new. The interior of the church must have been at risk as well because authorities removed the precious Arch of S. Corrado (the patron saint of Noto) and installed it for safe keeping in the church of S. Domenico. The 1727 earthquake not only damaged S. Nicolò. The facade of the church of S. Francesco broke apart, the vault of S. Agata fell, the cross of the church of SS. Trinità tumbled off, S. Maria di Gesù was damaged, and a portion of the facade of the Jesuit seminary facing the present Piazza XVI Maggio collapsed (Canale 1976, 58, 363, 288–89; Boschi et al. 1995; Gallo 1964).

The 1727 earthquake should have proven to the people of Noto that seismic events recurred and that they were extremely dangerous to masonry structures. Yet no evidence of antiseismic construction techniques appears in the first church of S. Nicolò, badly damaged in the earthquake of 1727, even though this first church was built within memory of the great earthquake of 1693. Just the year before, in 1726, a major earthquake destroyed scores of buildings in Sicily's capital city of Palermo, only a few days ride from Noto. Palermo had initiated some surprisingly avant-garde antiseismic construction methods (La Duca 1995). For example, after the 1726 Palermo earthquake we know that antiseismic solutions for domes made of stucco and wood instead of stone were discussed and implemented. Strengthening of damaged structures through the copious use of iron was introduced. Even a law prohibiting the use of heavy balconies was promulgated.

What effect did the lessons of the Palermo earthquake of 1726 and the earthquake of 1727 have on reconstruction in Noto? An aristocrat writing Noto's early history states that after the earthquake «the walls of convents, palaces and churches were in such poor condition, so full of fissures, that they had to be repaired either with buttresses or iron chains.» Variations on these techniques are used after earthquakes in present day Sicily. Rosario Gagliardi, the most famous architect working in 18th century Noto, must have known about how to built antiseismically. For example, Gagliardi was employed as the architect of the new church of S.

Maria la Rotonda in 1730 in which the walls were strengthened with iron rods. Twenty years later in 1750 in an assessment of the church of S. Michele in the Sicilian town of Scicli he proposed two solutions to roofing in relationship to earthquakes (Nifosì 1988, 32, 37). He advised that light vaults of wood and cane and plaster would resist earthquakes more effectively than stone arches. Gagliardi's discussion of vaults in Scicli proves he was cognizant of seismic hazards and understood antiseismic strategies. Yet no seismic strengthening is recorded at S. Nicolò. While workers seem to have been repairing the «pietra d'intaglio» [ashlar masonry] of the «arches, pilasters, and windows», Gagliardi was employed to take down and to remount the bells of the church. It seems that Gagliardi was adding a single belfry to the facade, perhaps a miniature or full-scale tower façade. What is not described are the antiseismic iron rods or chains he used in S. Maria la Rotonda. Instead, the upper part of the facade, probably ruined in the earthquake, is remade. It is difficult to judge this work in relation to seismic safety.

Between October 8, 1745 and August 21, 1746, for reasons still unclear, the campaign to finish the first church was abandoned and an entirely new church begun. Perhaps the earthquake of 1727 had dealt the first church a fatal blow, the extent of which experts only realized over time. It is possible that the initial damage caused further failures much later just as the damage from the 1990 earthquake contributed to the failure of S. Nicolò in 1996. Social and aesthetic reasons could also account for the abandoning the 1696 design. Perhaps the first church, still incomplete, was insufficiently large or grand in relation to new mother churches being erected in other cities of southeastern Sicily. The new second church begun in the 1740s was designed encapsulate the nave of the first church. Documents record that stone is delivered to the site as early as 1746. The shipments of stone are presumably for the new walls for the apse and chapels being built at the northern end of the church, which could be built while the facade and nave of the first church remained undisturbed.

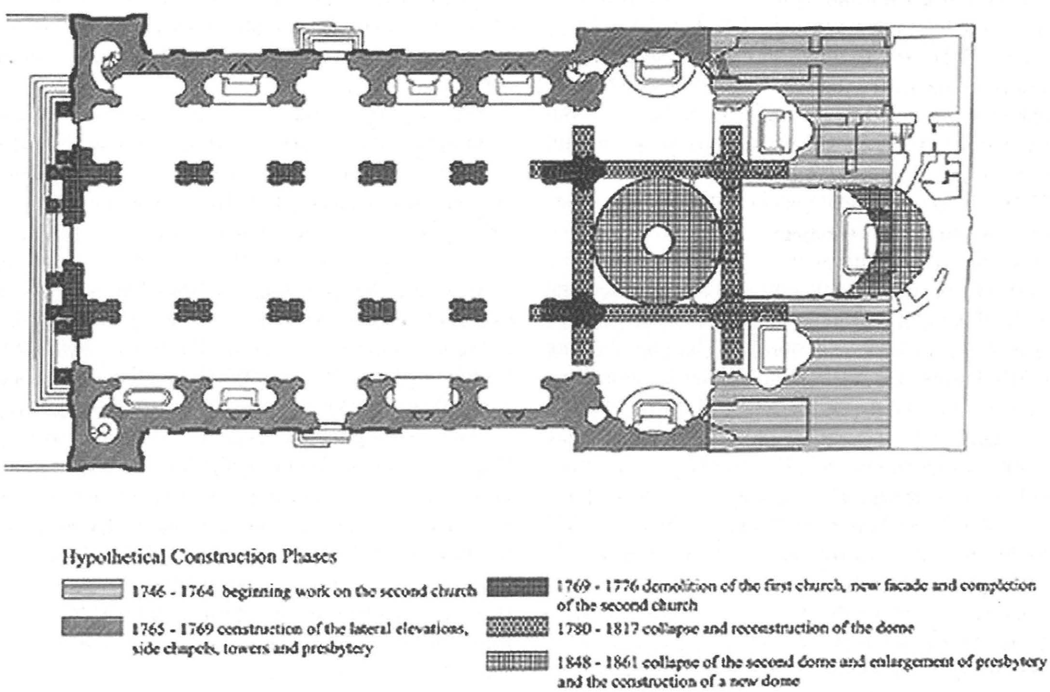

Figure 2
S. Nicolò. Plan illustrating successive building campaigns (drawing: Emanuele Fidone)

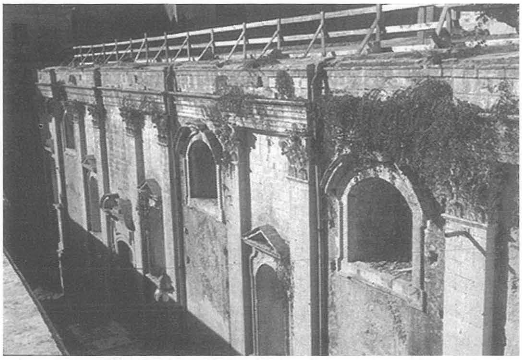

Figure 3
S. Nicolò. Detail of lateral elevation (photo: author)

Figure 4
S. Nicolò. Interior as seen from remains of roof at crossing (photo: author)

Authorities called in Gagliardi in 1753 to render an expert's opinion as to the condition of the first church. The question was whether to reutilize the nave and facade of the first church or finance new construction. Gagliardi strongly condemns the construction and aesthetics of the entire first church in order force church authorities to finance a new building. Gagliardi writes «internally and externally I declare the building to be false to architecture without the possibility of being able to be brought to any approximation of proportion or architectural perfection. Second, you can't vault it because the walls are very weak and full of holes . . . In my view the church should be demolished and so the new church, which one can see is already underway, and rises with a fine and regular sense of architecture can be built.» Gagliardi's condemnation of the structure and the architectural design of the first church is a legal document and must been taken extremely seriously. That he did not exclude his own work on the facade is surprising, since his condemnation could be legally binding, inferring that the architects who had directed the works (himself included!) would have been financially responsible for the shortcomings of the building. A second document of Oct. 1, 1753 complained that the walls were improperly constructed of «pietra molle» (soft stones).

After initial reluctance the church officials endorsed the new second church. From 1764 to 1769 work began on the chapel of S. Corrado, the chapel of the SS. Sacramento, the left campanile and the right lateral elevation of the second church.

The lateral right wall was laid outside the perimeter of the nave of the first church, which was still intact, Figure 3. Both the right and left lateral elevations with their dynamic rhythms, expressive decorative features, and quality of surface and depth are in the style of Rosario Gagliardi. Between 1769 and 1776 the old church in the interior of the new walls was demolished, and the new interior with piers to support the clerestory, the façade, and dome were constructed.

Although his name is never mentioned in the documents, the author of the plan and original elevation for the second church of S. Nicolò is probably Rosario Gagliardi. The plan of the church is very close to a number of variants of a basilica plan attributed to Gagliardi as well as to other buildings he designed like SS. Crocifisso in Noto. Only in 1767 is the «architetto» named, and he is Gagliardi's associate, Vincenzo Sinatra (Di Blasi 1990, 18). Before Gagliardi died in 1762 Sinatra had established a close professional relationship with him which was further strengthened when Sinatra married Gagliardi's niece. Working for Vincenzo Sinatra as his capomastro was Giuseppe Sinatra, Vincenzo's son by a previous marriage. By the time construction of the facade had begun Gagliardi's full Baroque style had waned in popularity and Sinatra toned down the facade, as his patrons, the aristocrats of Noto, would have wished. The second church was opened for services in 1776.

Several features of the second church of S. Nicolò (Figure 4) could have been attempts to make it

seismically resistant. The first possibility is that the lateral elevation of Gagliardi's project called for a building with excessive mass and a low height to width ratio which lowered the center of gravity. The massive lateral walls and deep chapels of the nave might aid the stability of S. Nicolò in an earthquake. The depth of the wall itself and its continuity with minimal apertures, combined with the interior walls, which link it the internal piers, provide resistance in two directions. Further, the buttresses above the lateral facades help stabilize the clerestory walls. The second possibility is that Gagliardi may have attempted to lessen mass bearing on walls. If the interior were vaulted in cane and plaster, exerting negligible thrust on the clerestory walls, the seismic threat to the structure would have been lessened. Gagliardi designed domes in Noto like the one atop the Jesuit church of S. Carlo, as «Lombard domes», with framed timber roofs and interiors of wood, bamboo and stucco instead of heavy masonry. The interior of S. Chiara has an intricately designed light stucco and wooden vault. In his work throughout Noto there is a lack of large domes, tower facades, or high towers. An acknowledgment of seismic problems might explain why Gagliardi's church of S. Domenico is unusually squat and why he adopted the method of miniaturization in his tower facade churches which reduced how far the last story projected above the roof. Because S. Nicolò was the Chiesa Madre, it required a dome. The kind of dome favored by Gagliardi is illustrated in his design for S.

Figure 5
S. Giorgio, Ragusa. Elevation. Rosario Gagliardi (Archives of S. Giorgio, Ragusa)

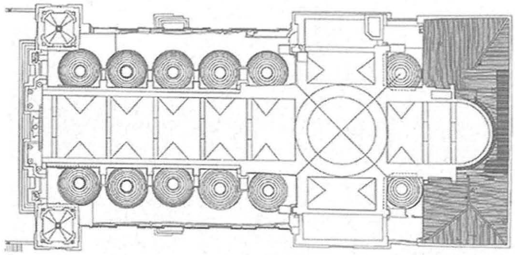

Figure 6
S. Nicolò. Plan illustrating discrepancy between buttresses and transverse arches (drawing: Emanuele Fidone)

Giorgio in Ragusa Ibla of 1738 (Figure 5). This dome with its modest cupola, low drum, and heavy walls is extremely conservative. Unfortunately, like all domes whether they be masonry or steel, this one would have been at risk in earthquakes.

Several puzzling changes, perhaps related to earthquake damage, occurred in the nave during the construction of this second church (Figures 6 and 7). The internal transverse arches are not aligned with the exterior buttresses. How can this strange inconsistency be explained?

One could hypothesize the presence of a truss roof which was built in relation to the external buttresses, perhaps designed for a lower stone vault in a first campaign, around 1770. This solution was then changed to the one we see today. They decided on a higher vault in cane and plaster with the transverse arches in stone which are off-axis in relation to the buttresses. The builders could have decided to alter their original design for aesthetic or structural reasons. It is possible that the building may have been damaged by the earthquakes of 1666 and 1667 which struck Noto. It is also possible that cracks appeared in the piers of the building, causing builders to rethink the design for the clerestory, roof and vault. If this hypothetical change did occur, the diminishing of the weight of the vaults could be seen as an antiseismic strategy, but the off-axis arches introduce torsion into the structure because of the irregularity of the load path.

The ruins of the second church of S. Nicolò (Figure 8), and the documents related to its construction are in accord: This was a masonry building built in the tradition of Noto (Fianchino and Sciuto 1999, 71–82,

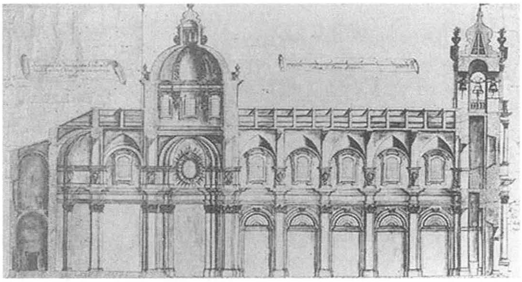

Figure 7
S. Nicolò. Exterior buttresses (photo: author)

100–124). Like other Noto buildings S. Nicolò is entirely stone, without a single brick. The stones called out in the documents are the stones which were used in other buildings (Fianchino 1983, 74–75). Some are quarried from the site of the city and others are brought from quarries nearby. They include various grades of sandstone and limestone (Emmi and Realini 1996, 111–120). The construction techniques are similar to those described by Giovanni Biagio Amico (1684–1754) in his treatise *L'Architetto Prattico* (1726/1750) and detailed by modern scholars of 18th century Sicilian architecture (Cottone 1987, 81–86). Amico writes that among the various kinds of walls «There is also another way of making encased walls . . . in which the exterior is constructed of squared stones and linked together with other squared stones keyed are right angles, and filled with stones and earth, or mortar. In Sicily they use mostly uncut and roughly cut stone, filling the remaining voids with small stones and mortar with finely hammered lime (Amico 1726/1750, 1, 63).» This stone masonry technique, described by Vitruvius, was well known in Antiquity. The ruins of the exterior walls of S. Nicolò clearly illustrate the use of irregular stones placed in rough rows inside an outer ring of cut stone, » pietra d'intaglio.» This technique was common throughout southeastern Sicily as a comparison between S. Nicolò and the Monastero dei Benedettini of Catania demonstrates (Barbera and Lombardo 1989, 20–25). The ultimate stability of the mass of stones depends upon the strength of the mortar and if all else fails on the ashlar masonry skin of the wall.

In the last campaign to finish the nave of S. Nicolò stonemasons made a major miscalculation in the construction of the nave piers which nullified any attempt to make the building safe in earthquakes. The static loads of the clerestory, side vaults, nave vaults, and dome are all carried by the piers, so their construction is particularly important. But in S. Nicolò the nave piers are the weakest part of the entire building because of one mistake, the use of round river stones in their construction (Figure 9). While river stones are excellent in compression they are smooth and round making it difficult for mortar to adhere to them. As architectural treatise writers uniformly advise, they must be broken up if used in walls. To do otherwise is to build a structure that violates the rules of good architectural practice (Alberti 1988, book 3, 8, 11). After the Calabrian earthquakes of 1783 authorities condemned the use of round river stones in walls as being one of the causes

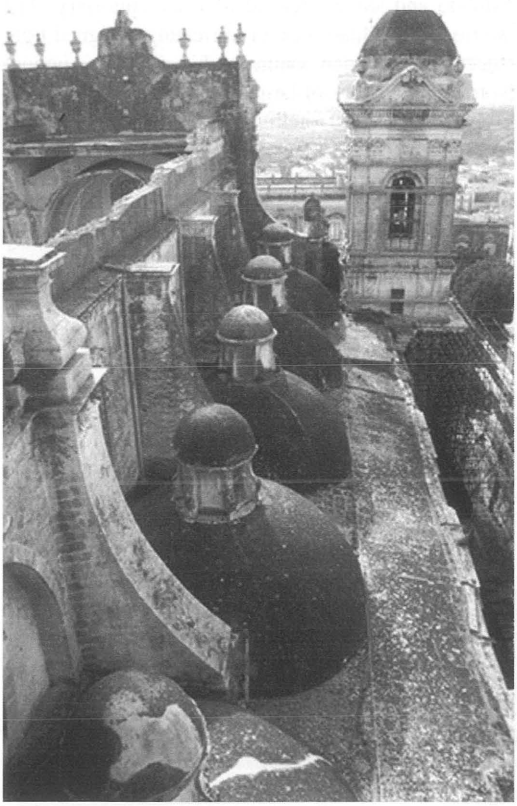

Figure 8
S. Nicolò. Interior with broken piers on left (photo: author)

Figure 9
S. Nicolò. A broken pier illustrating river stones in core and cut stone facing (photo: author)

for building failures in earthquakes (Tobriner 1983, 135). The Bourbon government of Naples prohibited the use of uncut river stones in all new construction in Calabria.

The mistake of using round river stones in the piers is compounded by the use of poor rubble limestone and weak mortar and an even weaker external ashlar revetment (Binda et al. 2000a, Binda et al. 2000b). The mortar in the piers is not particularly strong and was not viscous enough to penetrate between the rubble. As a result there are unfilled holes in the cores of the piers. The stones in the core are of poor quality as well. In fact, except for the river stones, Gagliardi's description of the construction weakness of the first church, and his accompanying condemnation of the same year, fit the description of the construction of these piers and the stones of which they are composed. The exterior «pietra di intaglia» had the potential of confining the problems of the core. But only one thin width of cut stones was laid. Unlike designs advised by Vitruvius, which were supposed to be made of chains of stones, here there is but one width of poorly bonded stone. To make matters worse, the design of the piers had indentations for niches which induced the masons to lay stones which in some cases touched only at the corners. The miracle is that S. Nicolò stood as long as it did.

How can the poor construction of the piers be explained? It should be noted that the piers, nave roof, and dome were the last part of the building campaign, coinciding with the demolition of the old church. The upper parts of the church are better crafted with material superior to the lower. The demolition of the old church would have produced a great deal of material which would have had to have been carted away. Gagliardi's condemnation of the first church was long forgotten. Perhaps material from the first church was reused in the piers to simply use it up. The river stones, too, were probably on the site. Perhaps there had been an overrun and these stones were extras. So to use up unwanted material the bases of the piers were begun with river stones and soft lime stones. There also could have been unsupervised filling of the carefully cut exterior perimeters of the piers. Master masons set the cut stone (pietra d'intaglio) while day workers may have been responsible for filling the interiors. Hence the mistake.

Another possibility exists which is linked to the reluctance of the aristocrats to fund the project and the anxiety of the populace regarding their unfinished Chiesa Madre. After the initial ardor to complete the building, enthusiasm waned. In the 1740s and 1750s aristocrats appear to have been reluctant to fund the project. Instead they concentrated on their own churches and chapels. But by 1770 the funding outlook brightened. A document of 1770 enumerates an aristocratic bequest of funds to the Chiesa Madre that so inspired the populace that they donated not only their own money but their own labor, motivated by «un Santo Zelo.» What effect did this «zeal» combined with faith and impatience have on the construction of the church? Is it possible that the citizens of Noto were moved, like the aristocrats and commoners of the Miracle of the Carts in Medieval Chartres, to carrying stones to the construction site of the Chiesa Madre. Could these stones have come from the Asinaro River which flows near the site of Noto? Faced with the pious donation of mounds of inappropriate material, and the further donation of free unskilled labor, perhaps the capomastri headed by Giuseppe Sinatra made disastrous misjudgments. Yet another possibility is that seeing the poor quality of the rubble limestone available for the filling of the piers the capmastro decided that stronger limestone, even in the shape of smooth river stones, was better than nothing. Understanding the problem he interspersed the river stones with the other fill in the piers.

The piers may have begun to show signs of weakness during construction. The vertical cracks discovered in the piers by Luigia Binda and her group of researchers indicate they were spreading and buckling under vertical gravity loads at least as early as the re-plastering of the church around 1950 and most likely before (Binda et al. 2000b). Could the cracks have alarmed the capomastri sufficiently for them to attempt to diminish the load by lightening the roof? Could this explain the puzzling change in the vault design? We will never know.

S. Nicolò's construction history is complicated still further by the failure and reconstruction of its dome. While a detailed history of the domes of S. Nicolò is not germane to this essay an assessment of their possible antiseismic qualities is. The dome of the second church, the first dome, was badly damaged in an earthquake on June 5, 1780. The dome collapsed and the remains of both it and the apse were demolished by late June. In 1789 the French traveler Léon Dufourny describes work under way to build a second dome. According to Dufourny, the architect Stefano Ittar was in charge of the works. Dufourny explains that Ittar was diminishing the dimensions of the windows of the crossing and reshaping them as ovals in an attempt to provide better support for the dome. Dufourny is dubious that this strategy is sufficient to correct the problem. Since Ittar is never mentioned in the documents, it is possible he left the project which was then executed by Bernardo Labisi, the son of Paolo Labisi, who appears in the cantiere of S. Nicolò as an architect in 1809 and an engineer in 1809 and 1813. By 1816 windows were installed and by 1817 the dome was plastered. In 1818 another earthquake damaged the new second dome. It was evaluated for possible repairs in 1839, only to be shaken to ruins in 1848. The third dome was begun by Luigi Cassone in 1857 and completed in 1861.

Unfortunately, information about the first two domes is extremely limited, and even the design process of the third is unclear. Still the question can be posed whether there is any evidence of antiseismic construction features. In other words are there any special design features or reinforcement strategies particular to antiseismic design? Several possibilities emerge. The first involves the partial filling of the nave windows (Figure 10) at the crossing before the installation of the second dome that Dufourny ascribes to Stefano Ittar. This tried and true method was used many times before. For example, after the second dome of Hagia Sophia partially collapsed in an earthquake in 984 four windows were closed to consolidate it (Mainstone 1997, 89–99). Ittar may have also designed the buttresses of the crossing below the dome, which are built of inclined cut stone to effectively counter the thrust of the weight of the drum. The beautiful stonework thoughtfully laid to counter the lateral thrust contrasts markedly with the work in the rest of the building. Another example of antiseismic considerations was the unsuccessful attempt by Cassone to limit the weight of the third dome by using pomice stone. Unfortunately the stone could not be obtained. Professor Maddam of the

Figure 10
S. Nicolò. Oval window and buttresses at crossing. In the late 18th century the original aperture was diminished and a smaller oval window inserted to add strength to the crossing (photo: author)

University of Catania advised Cassone to use brick and strong pozzolana mortar for the dome, which would have yielded a stronger structure than Noto's typical mortar and stone construction but this suggestion was not taken.

What could have been done to improve the performance of S. Nicolò? Masonry is extremely rigid and brittle and therefore vulnerable seismic damage. A masonry structure is composed of thousands of pieces bound together by mortar. The challenge is how to aid a masonry structure to move as a unit without breaking apart. In relation to domes, the famous treatise of Giovanni Poleni, *Memorie istoriche della Gran Dome del Tempio Vaticano. e de'danni di essa, e de' ristoramenti loro* (Parma 1748), would have been a useful source for the builders of S. Nicolò. Poleni explains the mechanics of dome failure and discusses counter measures like the use of iron chains to control the thrusts of domes. Poleni's analysis the effectiveness of the iron bars and chains used in St. Peter's dome in relation to earthquakes is extensive. Iron rods had been used by Brunelleschi in his Ospedale degli Innocenti in Florence to control the splaying of arches (Saalman 1993, 40–48). In the 16th century Giacomo della Porta used iron rods to control hoop forces when he was completing the dome of St. Peter's (Robison 1988, 257). Later in the 17th century Francesco Borromini used iron chains to counter the thrust of his complicated dome of S. Ivo alla Sapienza (Connors 1996, 680). Iron was used by the Perrault in the 17th century in the eastern facade of the Louvre (Berger 1993, 65–67). It was iron that was recommended as an anti-seismic measure after the earthquake of 1751 in Gualdo Tadino, Umbria (Tobriner 1997). Giovann Battista Mori recommended iron reinforcement after the Calabrian earthquake of 1783. When the church of S.Maria degli Angeli in Umbria was badly damaged in an earthquake in 1832 its dome was repaired with bands of iron and the entire reconstruction was tied together by iron straps (Mancini and Scotti 1989). But there is no such reinforcement in S. Nicolò.

It is important to remember that S. Nicolò was being reconstructed during a period in which earthquake resistant construction was known, even in Noto. In a treatise of Christian Wolff's *Elementa Matheseos Universae* (1715–17) translated for Paolo Labisi in 1746 as *Elementi dell'Architettura Civile* there is a discussion of lateral bracing in roof systems and a depiction of the «craticola» used in foundations which served «ad impedire ne' tremuoti lo scompaginamento delle parti» (Tobriner 1997, 34–37). Books and articles on antiseismic design (Di Pasquale 1986; Lanier and Barbisan 1996; Barbisan and Lanier, 1995) like Eusebio Sguario's *Specimen physico-geometricum de terraemotu ad architecturae* (1756) were in circulation and because of the earthquakes of Lisbon in 1755 and Calabria in 1783 discussion of seismic problems became more common in the 18th century (Placanica 1985). Francesco Milizia in his *Principii di Architettura Civile* (1781) discussed antiseismic construction strategies (Di Pasquale 1986). Common sense solutions for limiting a building's exposure to earthquake damage like building its dome in cane and plaster, reducing the dome's height, or eliminating it entirely seem never to have been discussed in Noto. Such changes in traditional practice are not without precedent: After the earthquake of 1783 the Bourbon government of Naples limited the height of buildings because of seismic danger. Yet we can well understand the problem the people of Noto faced. It is unthinkable that the Chiesa Madre, much less the Cathedral not have a dome.

Instead of improving the performance of S. Nicolò, 19th and 20th century alterations may have accentuated the inherent weakness of the structure. With the elevation of S. Nicolò to the status of Cathedral came the necessity to create an even more exalted architectural statement. The chancel and apse were extended and the stone arches of the transept added. Of course the status of a Cathedral called for a high dome so when the last reconstruction occurred the engineer in charge, Luigi Cassone, complied. Twentieth century alterations followed the pattern of the 19th century. Church officials attempted to stabilize the Cathedral by adding a flat concrete roof which prejudiced the structure in two ways. The weight of the roof was added to the structure and the tops of the former transverse arches were cut (Figure 11). Rather than improving the performance of the structure by providing a stiff diaphragm to distribute the loads, the roof may have aggravated the situation. When one side pier failed instead of a localized failure, the roof spread the damage by transferring load to the rest of the nave, and thereby collapsing the entire interior.

Figure 11

S. Nicolò. Collapsed roof showing 20th century alterations. In the 1950s transverse arches were cut, clerestory walls heightened and concrete and steel roof with parapets added (photo: author)

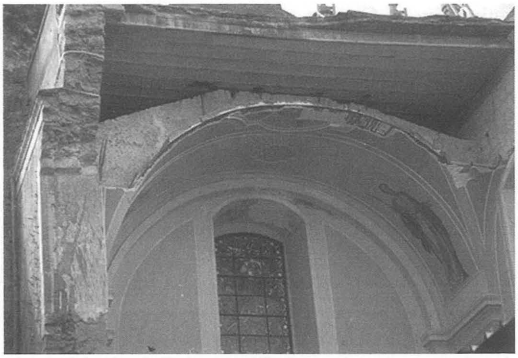

Figure 12

The Cathedral of S. Nicolò is an important and paradoxical symbol for the city of Noto. It represents the Noto that aspired to be a center of culture during the waning years of the Baroque style in the 18th century. It records Noto's last transformation in the 19th century into an aspiring ecclesiastical power. Noto's citizens as well as the Church attempted to use the new Cathedral to capitalize on religion to bring prosperity to the city. The Cathedral in the 19th century embodied a memory of past importance of the 18th century as well as Noto Antica. On the positive side, the reconstructions symbolize Noto's resolve to exist and continue as a city. Technically, there seems to have been pride and faith in traditional unadulterated stone masonry that was replaced again and again after earthquakes with little change in technology. One wonders whether the architects took failure for granted, realizing that it was likely that the exterior walls, side aisle domes, and nave arcade would survive while the dome and part of the crossing would likely fail. Perhaps they felt they could do no better. Less positively, the reconstructions could be seen as repetitions of failure without significant innovation or care taken to find a more appropriate solution. These reconstructions seem to indicate a lack of interest in the challenges that must be met when building in earthquake-prone Sicily. The history of the Cathedral of S. Nicolò is a story of tenacity and enduring tradition, but also of disregard for the lessons of the past.

Notes

1. This paper represents a summary of the studies in Tobriner et al. 1998. All cited dates and documents relating to the Cathedral of Noto are from this reference. The entire study is scheduled to appear as the first issue of a series to be published by the Architecture Department of the University of Palermo. An earlier version of this paper was submitted to *Construction and Building Materials.*

Industrialized log building by the Christoph & Unmack Company in Saxony (1907–1940)

Jos Tomlow

Among historical construction, log buildings generally are considered to be somewhat primitive and of rustic appearance. The log building system (in German: *Blockhaus*) in its origin shows walls of piled horizontal trunks, which in the corner interlock with the trunks of the adjacent wall. Log buildings, however, built in many forest regions since archaic time, were appreciated by its users for the positive heat insulation properties. In the early 20th c., a sophisticated technical development of log building in Niesky (Saxony) made the *Christoph & Unmack* Company (C&U) a leading firm for industrialized wooden housing.

Research at the Building Department of the Hochschule Zittau/Görltz (FH) for this paper —paralleled by an increasing general interest for C&U and its chief architect Konrad Wachsmann (1926–1929)— includes comprehensive archive studies and investigation of numerous buildings in Niesky.

After introducing historical wood housing of the region and the firm history, including works by the architect Albinmüller, the paper focuses on the structural design, especially of the «director's house» by Wachsmann (1929). Technical problems like the high tendency of shrinking of the wood in the direction perpendicular to the trunk axis and fluctuating humidity of the wood related to the seasons, were mastered by solutions which consequently regarded the nature of wood material.

Log building in the Slavonic tradition (*Schrotholzhäuser*), 1500/earlier? – 1900

(Franke 1936, Gerner 1997, Prietzel 1997, Zwerger 1997)

In the middle European landscape around Niesky, including Upper-Lausitia, Silesia (Poland) and the Czech Republic, Slavonic log building was traditional. The early housing type built in the Slavonic influenced tradition are known as *Schrotholzhäuser*, what etymologically roots in beams which are hewn to smooth square logs, with a specific ax, called *Schrotbeil* (later the logs were sawn). Those *Schrotholzhäuser* that survived around Niesky date from after 1700 (Prietzel 1997). The beams or logs show general dimensions from 18 cm x 24 cm, with a length up to 12 m. Big quantities of wood are used in this building type and the fir trees, from which these big logs were taken, must have been quite old. Since fir is resinous the logs were protected naturally against rot or worms. Starting from stones as a foundation layer, the logs are mostly put on each other without any profile. Since they were freshly hewn, after being built, during the natural drying process, they tend to take the shape of the neighbours, and this mend that only simple joint filling like fatted wool, were thought necessary to make the walls weather tight.

On the other hand the system did not suffice on the long term. The joints became uneven because of different shrinking in log parts (most in the top region

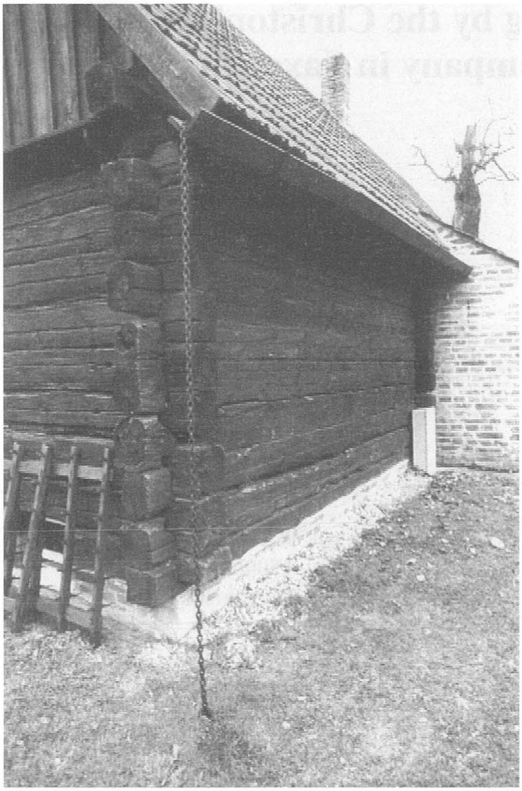

Figure 1
Schrotholzhaus in log building traditon, translocated to Rietschen, Saxony. The corner detail is of the ancient type with crossing logs (Jos Tomlow)

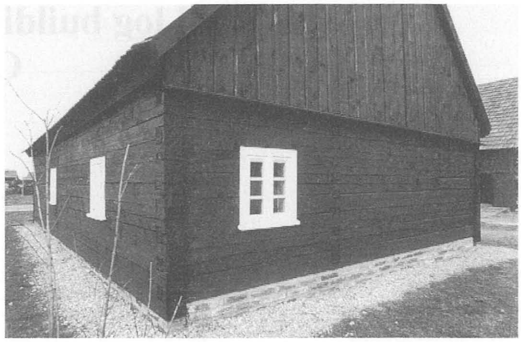

Figure 2
Typical *Schrotholzhaus* in Rietschen, Saxony (Jos Tomlow)

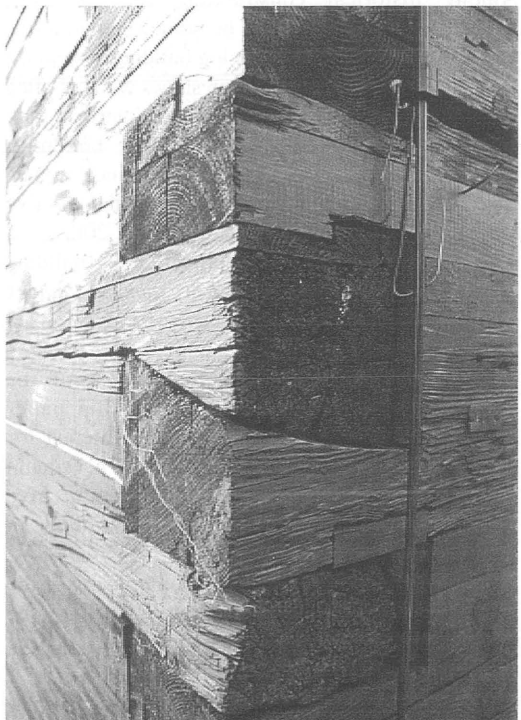

Figure 3
Typical corner detail of *Schrotholzhaus,* Rietschen (Jos Tomlow)

of a trunk) and this gave free play for wind and water. A dissolving of individual beam layers resulted and even real structural defeats occur, notwithstanding the thick dimensions of the parts and the repeated connections by long wooden nails.

Apart of the corner type with alternating crossing of the logs, many house corners show a smooth surface, what resulted from locking the beam ends in each other. Complicated carving became necessary for the smooth corners and yet this solution leads to exposed faces which are vulnerable for weathering.

Criticism is also inspired by the rather bad state of existing examples of the *Schrotholzhäuser*. My conclusion about this kind of log building, focussing on the mid-european climate, is: Despite complicated

corner details, they are technically vulnerable for defeats and not very intelligent in functional respect.

Figure 5
Settlement house *Blockaus Niesky III* of Christoph & Unmack in Niesky around 1920. Note cantilevered second floor (Jos Tomlow)

SLAVONIC LOG BUILDING MIXED WITH HALF-TIMBERED STRUCTURES (*UMGEBINDE*), APPROX. 1520–1900 (Bernert 1988, Delitz 1987, Franke 1936, Tomlow 200b, Zwerger 1997)

In the South part of the region, another house type became popular, which shows a mix of Slavonic one-story log building with an upper story of German type half-timbered houses. These houses are called *Umgebinde*-houses, after an wooden arch structure which carries the upper story independently from the log-room of the first floor. In this way the problem of log building of big and irregular deformations in walls caused by shrinking does not harm the upper floor and roof structure. To what extent the living area, built in the log system found historically a favorable reception —without doubt for its healthy interior climate— one can recognize from such cases where in a stone noble house such log rooms were integrated (Hauserová-Radová).

Some important renewals were established, compared to the log buildings described before. The log walls of the houses were thinner —f.i. half-trunks with the smooth side outwards and cladding by vertical planks inside— and better protected than in the *Schrotholzhäuser*, because of the cantilevering of the upper story. Another feature is that part of the walls is of stone in typical *Umgebindehäuser*. The reason for the stone wall is both to enhance structural stability as well as to give the house a more firm character. In other words, to give the impression that the wooden peasant hut is a «real» house. Often the entrance is a rendered stone portal with windows on both sides in a stuccoed wall. A third aspect of the stone wall parts is, that stables should be of stone rather than wood, which would not last long.

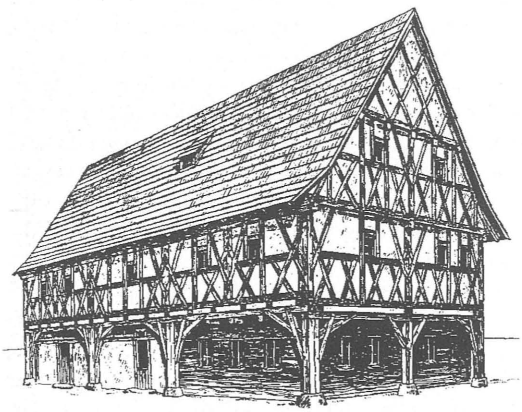

Figure 4
An *Umgebindehaus* from the Upper-Lausitia Region showing a mix of log building and half-timbered house (Loewe)

From a view point of building physics the *Umgebindehaus* is a highly interesting development, which will endure as a building tradition until 1900 with hardly any change in the basic concept. In comparison

to other housing traditions, which show a range of building types for different functions, the *Umgebindehaus* is remarkably differentiated in the climatic zones inside the house: A pleasant warm living and kitchen area is in the log part, stone walls border cool rooms, the half-timbered upper story house has good conditions for sleeping, whereas the extensively used roof shows a dry space to keep things long.

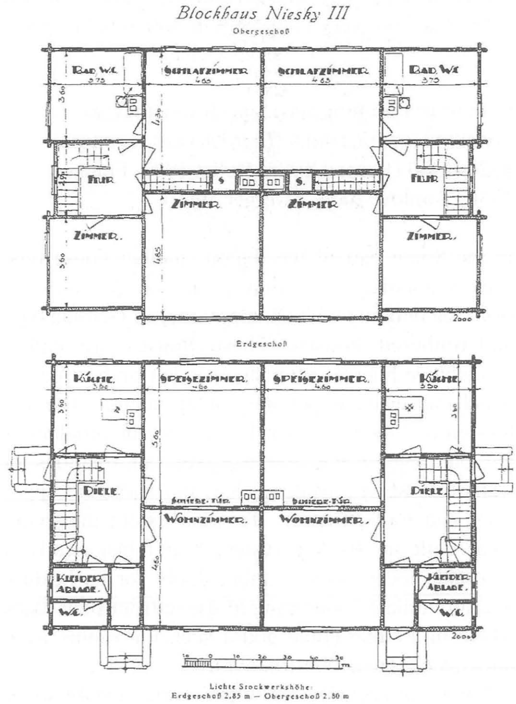

Figure 6
plans of double settlement house *Blockaus Niesky III.* (Nordische Blockäuser 1928)

C&U LOG BUILDING 1ST PHASE: FIRM-CATALOGUE HOUSES (*NORDISCHE BLOCKHÄUSER*), 1907–1940

(Hilger 1997, Hilger 1999, Junghans 1994, Katalog 2001, Nordische Blockhäuser 1928, Tomlow 2000a, Wohnhäuser 1940)

So, one can imagine how accepted wood housing in this region and in Germany was. Despite its traditional image, wood still kept in early 20[th] c an important part of the building material market. The use of modern machinery resulted in both high-precision dimensioning of wooden parts and in an extremely fast production, compared with traditional crafts. The Christoph & Unmack wood element firm in Niesky, about 100 km Southeast of Berlin, became the world's leading producer of prefabricated wooden houses. The vast production of Christoph & Unmack is still documented in about hundred dwellings in Niesky itself, dating mostly from 1920–1930.

The commercial success rooted in the purchase in 1882 of a patent on a barrack system, called *Döcker-Bauten* after its inventor, a Danish officer. The firm policy was, to add to the transportable barrack- like buildings of the *Döcker-Bauten* type, a complete new and huge market segment of «real» houses. Aesthetically, they wanted to give their barracks the appeal of a firm standing house, and they subsequently managed to open this brick —and stone—possessed market for the material wood. Among other building types, C&U started in 1907 the production of *Nordische Blockhäuser* of the log building type, which were inspired by both regional and Scandinavian traditions.

The new wooden log houses were presented in optimistic catalogues. They were built with beams and elements made on the basis of new high-precision fabrication methods. They were convincing in firmness, in the low material quantity needed and in low costs (fix prices). Because of the thin walls of only 7 cm logs plus interior cladding, they took about 20% less surface than a conventional house in brickwork.

The structural success of the logs rooted in a very sophisticated profile within dimensions of 7 cm thickness and 16 cm height. The logs were connected both by an exact fitting groove and wooden dowels. The edges of the logs were snubbed, what helped to concentrate the loads in the central part of the walls (avoiding splitting of the wood). The contact of the wall with the foundation —generally perfectly executed in brick, and often with a granite cladding— was established by a somewhat wider and thicker wooden element with an inclined top in the exterior part. For structural reasons, the corners were made with logs which continue over the corner point. The C&U firm concentrated all its know-how in the development of the details to find the right and structural sufficient dimensions, which were remarkably slender.

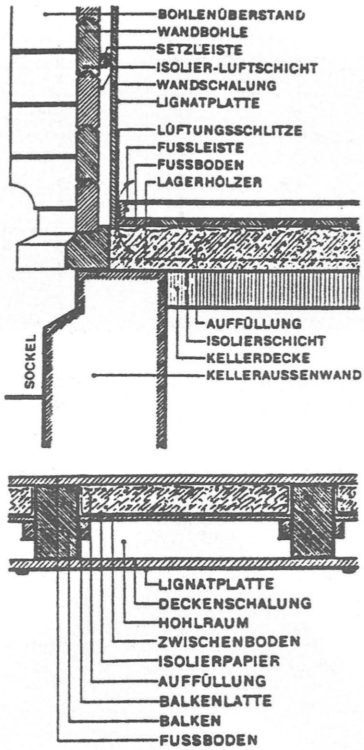

Figure 7
Christoph & Unmack, standard details of log building system for wall (Fig. 2) and ceilings (Fig. 3) (Wohnhäuser)

After an experience of soon 100 years the fire-authorities in Niesky are optimistic about these houses, since they hardly burn. Houses dating from the twenties or thirties which still stand, are generally sound. The rough wood was dried in open air and after this in hot-air halls in order to get a controlled low moisture level for the elements. Wood rot could be avoided both by structural details and with a low use of chemicals. Rain water was kept from the (air-ventilated) facade by lifting the entrance level some 70 cm or even more, and by using cantilevered roofs. Heating systems were chosen traditional which meant preferably no central heating and heating sources in only a reduced part of the house. Enough fire protection was established by keeping some distance between the individual house blocks —mostly semi-attached dwellings— which was in line with a garden city lay out of most settlements for C&U buildings.

From the view point of building physics many houses turn out to be almost sufficient (according to recent norms). Especially the use of the log building principle, with 7 cm thick massive walls of horizontal wooden beams, finished inside with planks, ensured a reasonable heat insulation, also in terms of acoustical insulation.

Recent modernization, which tries to «improve» the heat-insulation and acoustical properties often show bad results, since the houses stay what they are: «wooden houses»: introduction of plastic window frames in connection with central heating generates moisture problems. An extreme renovation example is a house in Niesky, which has a new cladding outside in brick (Hilger 1997, Hilger 1999). For half-timbered houses, in some aspects comparable to the log building type, quantified renovation solutions for heat-insulation exist (Lamers 2000).

From an esthetical point of view, the C&U houses of around 1920 gained compared to earlier examples and they show a natural timeless beauty. To my opinion this roots both in the professional marketing of C&U and in the fact that the intelligent design was structurally adapted to the material wood. Other wood building systems, like *Bauart Höntsch*, a firm which also had representations in numerous German and European cities, tried to copy stone houses of any style, hardly concealing the barrack system details, resulting in a product with less charm, to my opinion (Glaussnitzer 1924, Junghans 1994).

C&U LOG BUILDING 2ND PHASE: (*JUGENDSTIL*) HOUSES DESIGNED BY ALBINMÜLLER, 1914 APPROX. 1930 (Albinmüller 1921, Hilger 1997, Tomlow 2000a).

In the second phase, the firm, in a quite comfortable position because of its presence on the housing market, was eager to find cooperation with academic architects. Especially functionalist architects were also interested to work within the new industrial methods, as one nows from the building history of the experimental *Weißenhof Siedlung* in Stuttgart, 1927 (Tomlow 1998). Prof. Albinmüller (artist' name of Albin Müller) from the *Künstlerkolonie* in Darmstadt, was one of the prominent figures. Albinmüller started

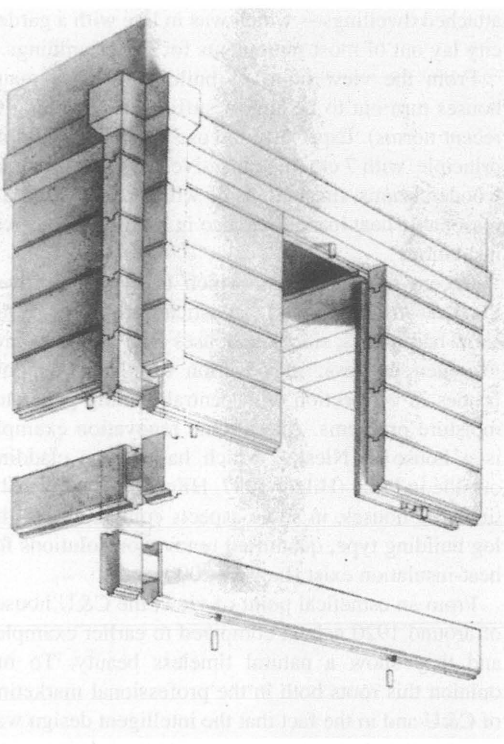

Figure 8
Drawing of Christoph & Unmack log building system. (Wachsmann 1930)

Figure 9
Albinmüller, Design for a forest house with cantilevering upper floor on three sides (Albinmüller 1921)

Figure 10
Albinmüller, bachelors' boarding house in the Plittstrasse, Niesky, 1923 (Jos Tomlow)

Figure 11
Albinmüller, corner of bachelors' boarding house in the Plittstrasse, Niesky, 1923. Note the carefull detailing of the cantilevering, making use of the floor beams rythm. The beam tops on the left side are structurally honest, whereas the ones on the right are short beams, suggesting symmetry (Jos Tomlow)

with designs for C&U houses in a romantic colorful *Jugendstil*. These designs, part of them in color reproduction, were published in Albinmüller's «*Holzhäuser*» of 1921, financed by C&U. This publication is an important step from the commercial C&U catalogues, towards the mature architectural theory in Wachsmann's «*Holzhausbau*» of 1930.

Albinmüller builds in this first period many houses, contributing original decorations, vaguely reminiscent of cubism. He introduced functional ideas like cantilevering wardrobes in the second floor facade of a bachelors' boarding house (1923, Plittstrasse 4, Niesky). In this boarding house, one can still find most of the original interior surfaces and one can look at stucco-imitating ceilings of a «rich» design of which Albinmüller was especially fond of (Hilger 1997). Technically the cassettes in these ceilings consist of wooden frame profiles, holding flat boards in between. In later times Albinmüller will build decent modern architecture in the C&U-systems, unfortunately loosing somewhat the material appeal of wood, for instance a restaurant for a theater exhibition in Magdeburg (Wachsmann 1930, 111)

C&U LOG BUILDING 3RD PHASE: (MODERN) HOUSES DESIGNED BY KONRAD WACHSMANN, 1925–1929

(Grüning 1986, Hilger 1997, Tomlow 2000a, Wachsmann 1930)

Wachsmann himself writes down his observations on the C&U firm in his book «Holzhausbau» (1930), a magnificent analysis of different building systems, starting from European and US-American traditions, beautifully presented in photographs and lay-out.

Historically highly relevant is that he illustrates the chapter on modern log building system with numerous photographs of the «director's house» building process (Wachsmann 1930, 31–37). A technical problem of the log building type, is the high tendency of shrinking of the wood in the direction perpendicular to the trunk axis. This tendency of shrinking is many times as much as parallel to the trunk axis, and Wachsmann calculates the shrinking of log walls with up to 10 cm per 3 m. Although this problem was already dealt with in earlier C&U houses (and even in the traditional *Umgebindehaus*), I will discuss it in connection with the presentation of Wachsmann's work for C&U. The solution that the C&U firm found, was to permit the story heights to shrink in a naturally way (f. i. from 300 cm to 290 cm). For this, of course, one had to prepare a perfect detailing with sliding parts over windows, door's and paneled walls and even with sleeves for vertical technical pipes.

Along the small facades the girders of the top floor structure protrude somewhat from the exterior surface, which again is due to structural soundness, avoiding concentrated loads on vulnerable end parts. Small metal caps avoid rain water introduction.

An important decision of the C&U firm —and proof of its far-reaching view— was to require the German patent of the Swiss product «Lignat». Lignat was a normally 6 mm thick board of rather big plate dimensions. Lignat consists of a material mixture

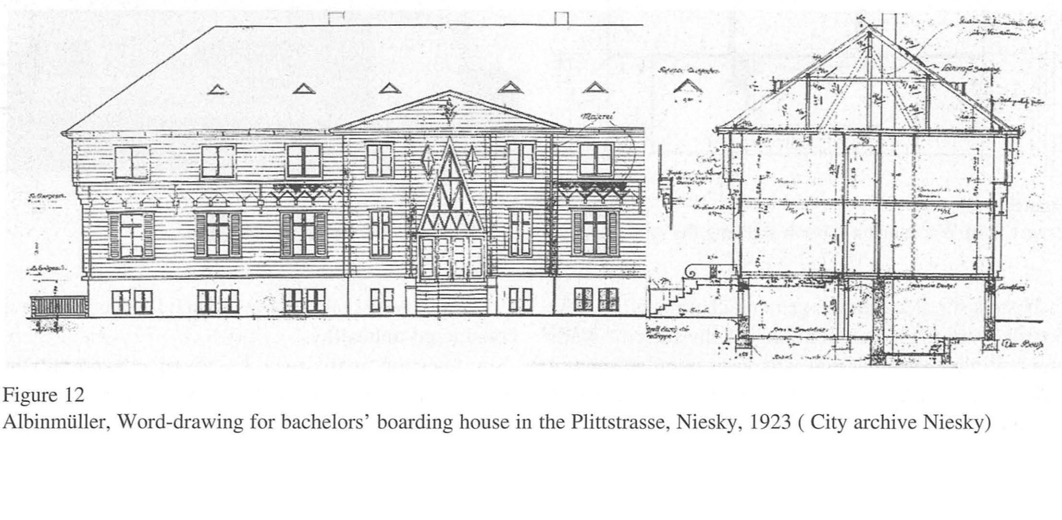

Figure 12
Albinmüller, Word-drawing for bachelors' boarding house in the Plittstrasse, Niesky, 1923 (City archive Niesky)

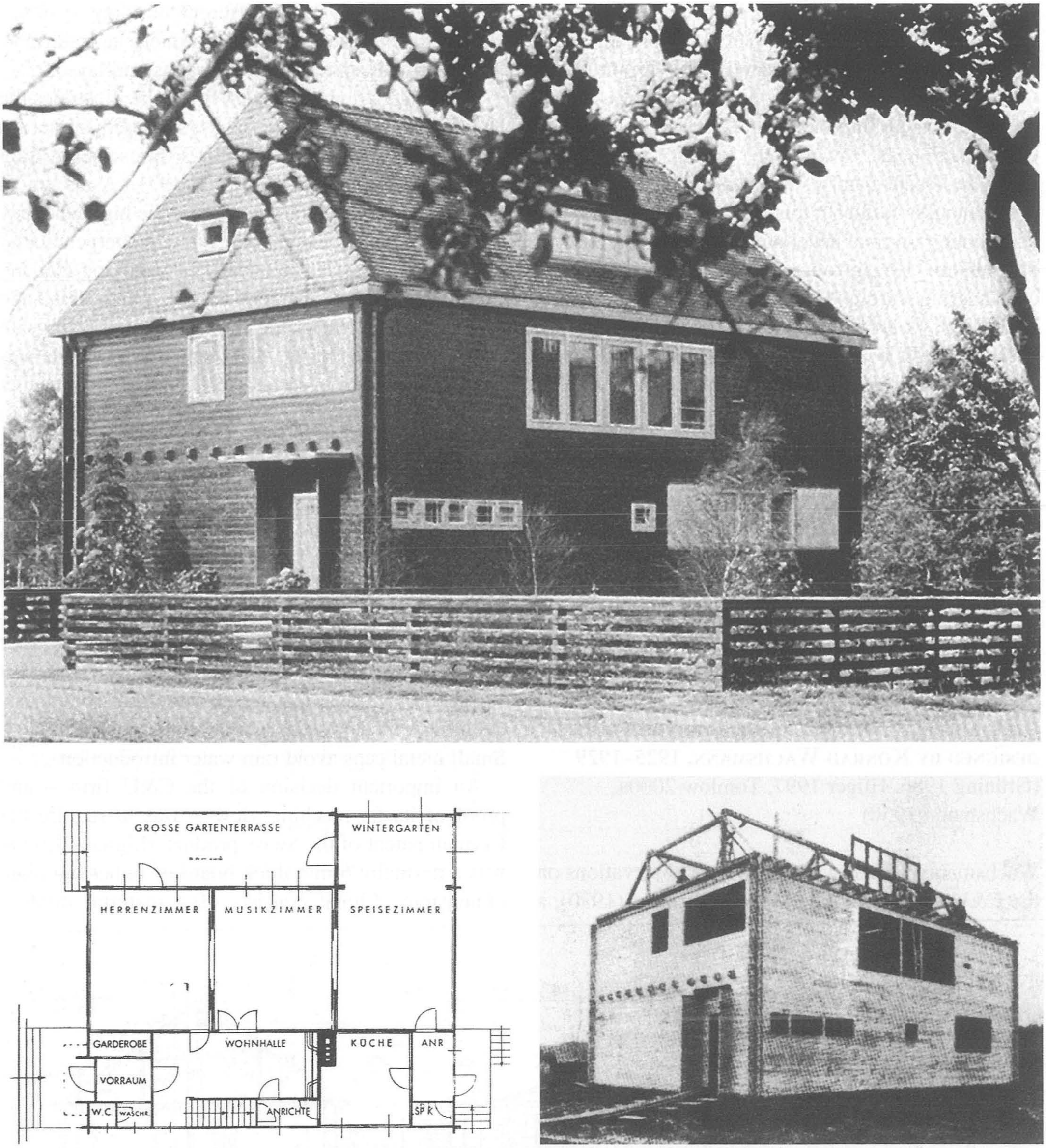

Figure 13
Page 133 of Wachsmann's Book showing the «director's house» in Niesky, 1929 (Wachsmann 1930)

(asbestos, shredded paper, cement, chemicals) and the boards were used as a cladding of the interior walls and ceilings. The material was very popular since it did not burn and it was not affected by moisture (Tomlow 1998).

Nowadays the fabrication of such fibrous cement is considered unhealthy.

A question mark may be given concerning the modernity of the «director's house», because its pitched roof is quite high, and some will think of

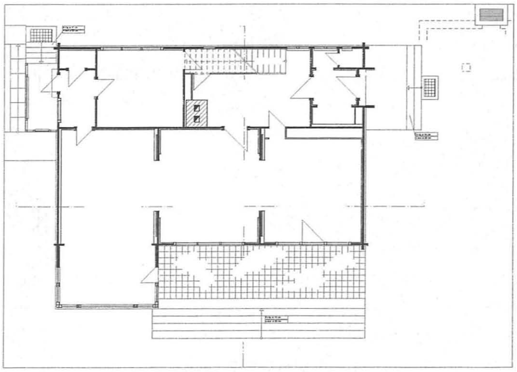

Figure 14
Konrad Wachsmann, frist Hoor plan of «director's house» (Measured drawing 2002 by Mathias Hennig)

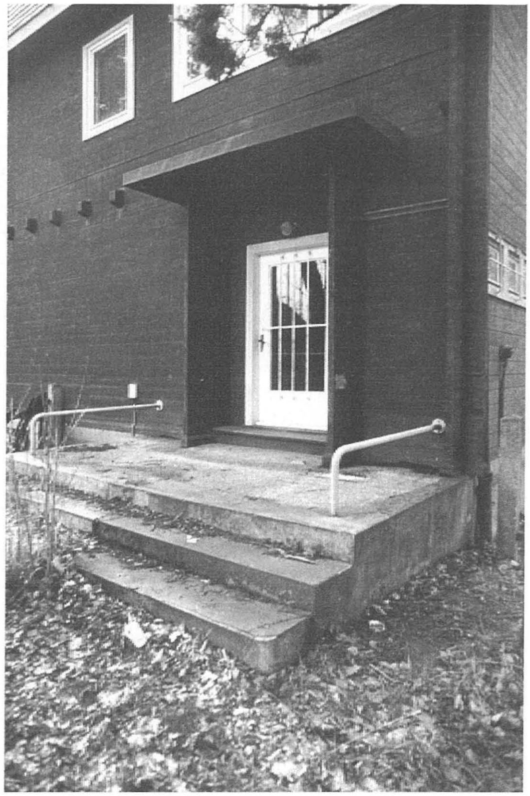

Figure 15
Konrad Wachsmann, entrance door to the «director's house» (Jos Tomlow)

conservative architecture of the thirties. Wachsmann himself accounts that he needed the roof's weight in order to keep the joints between the logs pressed together. On the other hand the four facades show a modern appeal, considering the year 1929, with a free and functional window distribution in an abstract geometrical lay-out. Remarkably are also the generous exterior stairs to front door and garden terrace (slightly different from the published plan). In the interior hall the landing of the stair and first floor balcony is consciously interrupted by the whitewashed volume of the chimney, which is thus free standing in order to enhance fire-protection.

The hall windows are concentrated in a 6 m long and 2 m high window series along the top end of the stair. These windows are beautiful from both inside and outside, but they are also the source of a structural defect in this house, similar existent in few other C&U houses. Because the exterior log wall of the hall is not stabilized by perpendicular walls over a length of some 7 m and, since the stair along this wall disconnects the floor structure from the wall, the wall tends to buckle. Because the material wood is «forgiving» such distortions of the wall surface are not fatal for the wall. Another reason for this kind of defeats is the behavior of wood to subsequently change form during long term loading.

Konrad Wachsmann's position in the C&U firm is not very clear from a historical point of view (Grüning 1986). On the one hand he builds the —for advertisement reasons very important— «director's house» and he publishes an important book with, again, a decent advertisement effect for the Christoph & Unmack firm. On the other hand, in the conventional C&U catalogue of 1928 his name or work does not appear. Maybe, one can ask, Wachsmann was too much of an individualist and too much a revolutionary constructor to keep in (slow) pace with the conventional thinking of the C&U firm? Sure is that he contributed modernity to the already existent honesty in structural design and freshness of the wooden architecture of C&U.

In 1930 Wachsmann opened an own office in Berlin, representing still the C&U firm. Konrad Wachsmann's influence on the products of the C&U firm is smaller than thought by scholars. However,

Figure 16
Konrad Wachsmann, rear facade of the «director's house» in Niesky, 1929 (Jos Tomlow)

without doubt Wachsmann's theoretical work —f.i. the publication of his book *Holzhausbau-Technik und Gestaltung* (Berlin 1930)— modernized the somewhat traditional, yet generally respected image of the firm. As an important contribution to the Modern Movement architecture may be regarded his own executed projects, f.i. the «director's house» (1929) for a chief engineer of C&U in Niesky, which is a log building. Other wooden buildings designed by Wachsmann for C&U, but not of the log building type, are: the famous Albert Einstein House in Caputh near Berlin (1929), an office of the B.V.G. Berlin (1928), a youth hostel in the *Riesengebirge* (competition entry), a *Kinder-Walderholungsheim* in Spremberg (child's leisure center), a tennis club in Berlin, and the geological institute in Ratibor (Grüning 1986, Katalog 2001, Wachsmann 1930).

During the thirties live and work in Germany became impossible for the Jew Wachsmann and he managed to reach the USA. In a fruitful cooperation with Walter Gropius a modernized version of industrialized wooden building can be developed: the General Panel System. Inspired by more research work as a teacher in the «New Bauhaus», the Institute of Design and the ITT in Chicago, he will become one of the world's most respected teachers of industrialized building and design. His publication: *Wendepunkt im Bauen* from 1959 is one of the key works on architectural design of the period (Wachsmann 1959).

One of the aims of this paper on Wachsmann's work for the Christopher & Unmack firm, is to save the existing houses, not only from natural decay —which seems the smaller problem— but also from misunderstanding by the present generation.

Acknowledgments

The paper makes ample use of a diploma work (civil engineer) by Käte Hilger *Systematik zur Baukonstruktion und zur modernen Sanierung von Holzhäusern unter Berücksichtigung denkmalpflegerischer Aspekte am Beispiel der Häuser von Christoph & Unmack (1920-1935) in Niesky* (typescript 1997) at the Hochschule für Technik, Wirtschaft und Sozialwesen Zittau/Görlitz (FH), consulted by Prof. Dr.-Ing. Christian Schurig and Prof. Dr.-Ing. Jos Tomlow. Sources for our studies were the city archive and the museum of Niesky, and the Rietschen *Ehrlichthof*. Thanks goes to students R. Böhm, D. Däumler, T. Haag from Weimar. My student Mathias Hennig prepares a diploma design for a wood building museum and research center in and next to the «director's house» in Niesky, a project in cooperation with Eva-Maria Bergmann of *Museum Niesky* and Hans-Joachim Tauch of the building department in Niesky. Special thanks goes to Karl Bernert, the specialist of the *Umgebindehaus*.

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The church of St. George in Velabrum in Rome. Techniques of construction, materials and historical transformations

Maria Grazia Turco

The episodes of terrorism which happened in Italy in 1993 —directed towards the buildings on Georgofili street in Florence, the building of Ignazio Gardella on Palestro street in Milan, the Loggia of the Benedictions in St. Giovanni in Laterano and towards the church of St. George in Velabrum in Rome, Figures 1–2— resulting in a vast damage to its architectural patrimony, has raised the immediate and important issue of restoration with its various solutions.

In the case of church of St. George in Velabrum political authorities wanted the reconstruction to erase the wound inflicted on its artistic and architectural patrimony. The people wanted, in fact, to reclaim one of the most ancient monuments of the city, situated in a place called *Velabrum*, where, symbolically speaking the history of Rome had its beginning with the rescue of Romolo and Remo from the «lupa» (wolf), or rather «Acca Larentia».

The subsequent restoration phase of the church has provided, through an architectural survey and the structural analysis of the construction, an intense study of the church and its successive historical phases. The analyses of the techniques of construction, of the materials, of the construction anomalies, the direct analysis of the masonries and the building elements have all helped to specify the different phases of a complex church like St. George in Velabrum.

We have proceeded with a reading of the archaeological type of the building front, with the

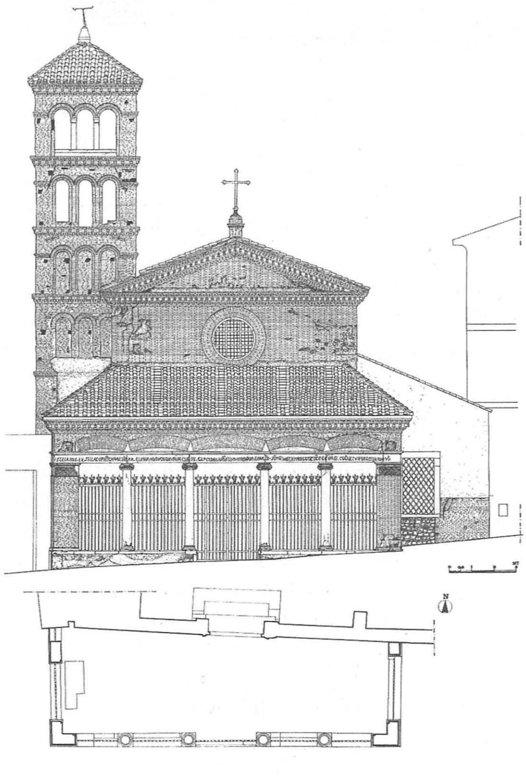

Figure 1
The front after the attack of 1993(Author's survey)

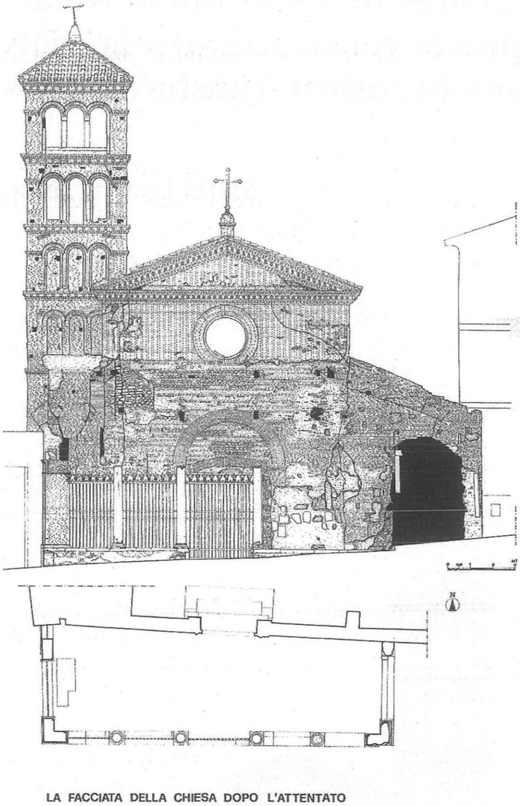

Figure 2
The front after restauration of 1993 (Author's survey)

purpose of individualizing the different building typologies and of clarifying the relationships of the parts through the analysis of the different building techniques. The examination of the façade has been privileged, with the fall of the plaster caused by the terrorist event, as has the examination of the bell tower, which is the key for the comprehension of the building's development. The study has faced the problem of the relationship with pre-existent Roman houses, before the actualization of the church.

The research on the building typologies has individualized a connection between the construction phases, from the foundation of the church in the VIIth century when Pope Leo II (682–683), on the pre-existing structure of a civil building of the classical age and a diaconate, consecrated the primitive church in memory of the two saints Sebastianos and George. In the IXth century (Gregorio IV 827–844) important changed the architectural structure of the church to its present day appearance. The portico was added in the middle of the XIIIth century as a donation of the prior Stephen Stella, testified by the incision on the architrave. Other interventions are realized in the XVth and XVIth century, Figures 3–4; Pope Clemente IX (1667–1669) intervened on the portico eliminating a span of it, Figure 5. During the XVIIIth century, after a period of carelessness, the church was the object of numerous transformations under the

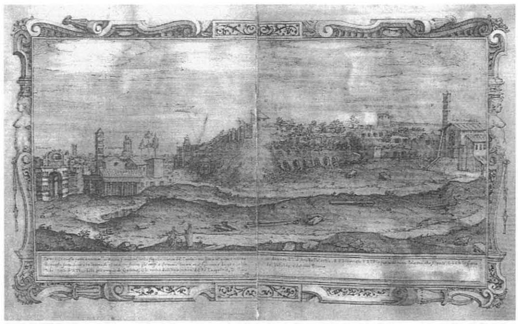

Figure 3
Etienne Du Pérac (around 1577). View of the Velabrum with the church of St. George and the Archs of the Argentaris and Giano (Du Pérac 1950, pl. 20)

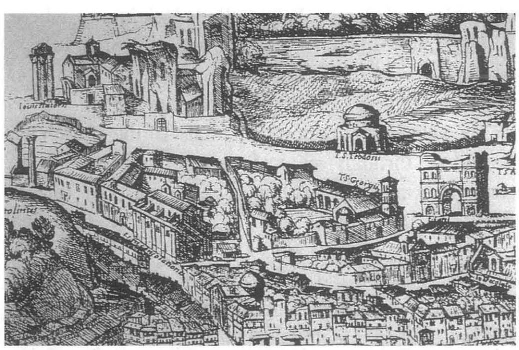

Figure 4
Antonio Tempesta (around 1593). The church and the convent of S. George in Velabrum seen by the apse (Frutaz 1962, pl. CXXXIV, 4)

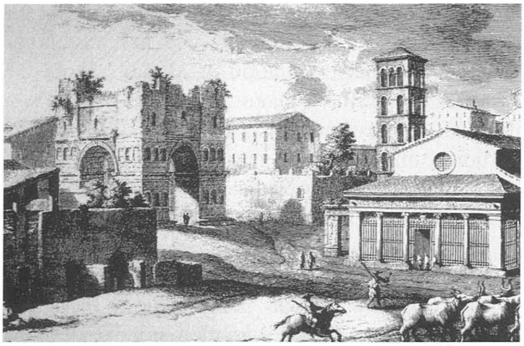

Figure 5
Giuseppe Vasi (1773). Image of the portico after the intervention of Pope Clemente IX 1667–1669 (Vasi 1753, pl. 55)

pontificates of Leo XII (1823–1829) and Pious IX (1846–1878); but Pope Gregorio XVI (1831–1846) proceeded with the elevation and the changing of the façade with the construction of the tympanum. Subsequently, in the years 1924–1925 Antonio Muñoz (Rome 1884–Rome 1960), Figure 6, proceeded with a radical restoration of the medieval *facies* of the church, removing the Baroque additions.

This study, a preliminary and fundamental moment for the following restauration of the church,[1] has been undertaken through the architectural survey and the morphological analysis of the building. The research during the survey has allowed the clarification of some moments of the church's building history and

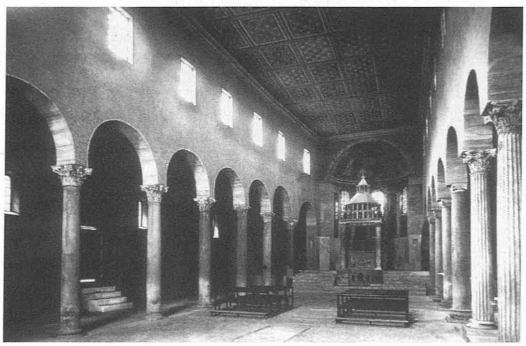

Figure 6
The church, inside, after the intervention of Antonio Muñoz (1924–1925) (Muñoz 1926, pl. XXXII)

the elaboration of a new hypotheses about the times and the ways the church was realized during the centuries. This is based on the direct analysis of the structures, made necessary and possible following the damages to the monument from the disastrous terrorist event.[2]

From here the scientific opportunity of the initiative of the Superintendence for the Environmental and Architectural Property in Rome to have the restauration proceed with ample research on the different construction aspects of the church, spreading to an ulterior verification of the existing written and documentary sources; also, the construction techniques, the materials, the construction anomalies and the identification of the preceeding interventions have been all recorded and evaluated during the survey phase. These elements, in fact, with the archived construction documentation, have constituted the base both for the evaluation of the condition of the building and for the consequent project.

Due to the analysis of the archaeological type of the façade, it has become possible to identify the diverse structures and to clarify their relationship; a sample of building structure just in those parts that had always been covered by plaster were able to be used arriving in this way to enucleate groups of homogeneous samples of materials, type of mortar and laying in work, such as to individualize single construction interventions.

The fundamental problem of the present study has been to specify the parts and the age of the original construction, a rather difficult enterprise as a result of the lack of documentary references and impossibility to excute excavations and investigations in the most ancient structures, discovered by Antonio Muñoz during the restauration in the years 1924–1925 (Muñoz 1926) and studied by Richard Krautheimer (Krautheimer 1971, vol. 1, 256–57).

According to Krautheimer, the church, built on pre-existing structures which explains the irregularities of the present building, had been definitely completed in the IXth century, as the *Liber Pontificalis* confirms (Duchesne 1892, 2: 79–80) in the biography of Pope Gregorio IV (827–844). The most significant building structure, discovered under the actual pavement, is surely a trace of a small apse, placed in front of the actual one, belonging to a complex of pre-existing buildings; the other

structures, discovered under the left colonnade and the right aisle, are, instead, traces of the foundation-walls of the ancient *schola cantorum.*

The very same complex building articulation has appeared in the front of the church, Figure 7, under the fallen plaster following the explosion caused by the terrorist attack. The wall has shown, in fact, a complex variety of structures, a testimony of interventions undertaken in different periods. The

Figure 7
The complex building articulation has appeared in the front of the church, under the fallen plaster following the explosion caused by the terrorist attack (Author's photo)

building sizing of the façade, up to the moment of the attack, had been known only through burdens photos taken during the restauration of Muñoz.[3] From the interpretation of these photos, historians have drawn different impressions, assigning only the building portion to the left in the façade to the IXth century, characterized by the irregular lines and the jade work of the building walls typical of that period, Figures 8.

The present study has confirmed that on the sides of the actual entry two openings are still traceable, situated at different quotas, already studied by Muñoz and Krautheimer, Figure 9: to the left we can see the window-post of an opening that still preserves traces of painting and its wooden lintel; the other wood beam that, on the top part, delimits another probable window, now closed, is identifiable at 2.00 mt from the left post of the actual portal. At 0.80 mt from the right door-post of the entry we have also found a third wooden lintel of an similar opening, even this is closed.

According to Muñoz, Figure 9, they are two windows (Muñoz 1926, 30): one on the left which portrays in the right window-post some painted circles; Muñoz considers this opening to reflect the original front of the church that was modified, taking on its present day appearance, probably during the same period as the construction of the portico, in the XIIIth century.

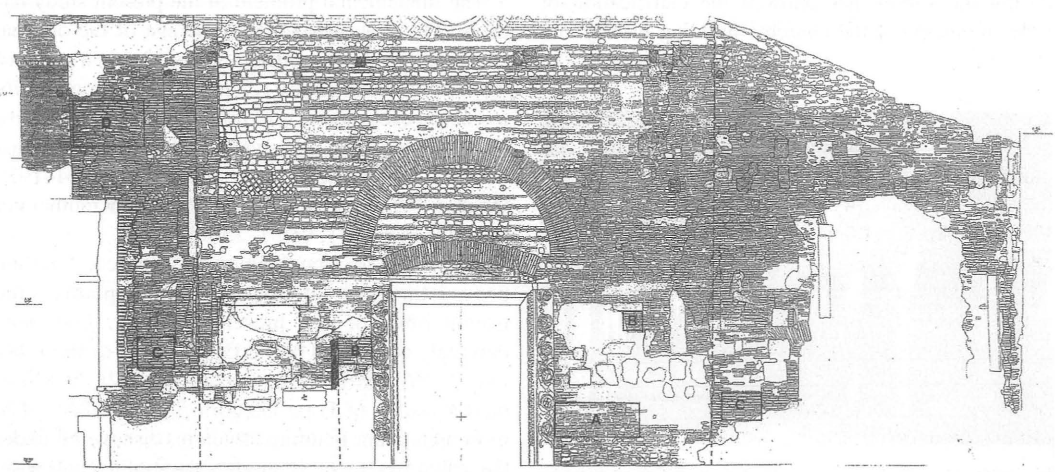

Figure 8
The principal front of the church up to rates 10.35 mt (Author's survey)

Figure 9
Hypothesis recostruction of the diaconate according to Antonio Muñoz (1) and Richard Krautheimer (2) (Author's graphic)

In that time the actual door was probably opened in place of the preceeding one that was smaller.

Instead, Krautheimer gives a different interpretation, Figure 9; he thinks that the opening on the left of the portal is not referable to an ancient window (Krautheimer 1971, vol. 1, 250). He considers it to be a door, probably, the original entry of the church.

With this study to third window has been discovered in the bell tower, on the left; façade structured in such a way, either as pointed out by Muñoz or as proposed by Krautheimer, that it is however referable to a pre-existent building, a common house or diaconate.[4] In conclusion we can affirm that the lower part of the actual front can surely be attributed to a historical period before the actualization of the church.

The front, therefore, up to the VIth century, Figure 8–A, at least in its lower extremity, is referable to a Roman laic façade as also testifies the good workmanship of the masonry, characterized by only bricks arranged in regular lines. The same form, of 5 lines of brick and 5 layers of mortar, that varies between 32–34 cm, also confirms the attribution of some lower building tracts on the right of the entry to the VIth century (Rovigatti Spagnoletti 1976–77, XXIII-XXIV: 124–25; 149).

After the VIIth century we Khan assumes that the façade of the pre-existing house was used for the construction of the church, with the opening of to new door and the closing of the window to left of the actual entry.[5] From the analysis of the bricks that close the two openings identified on the sides of the actual door we can deduce its attribution to the VIIth century, Figures 8–B, the period in which we can see the progressive lowering of building form due to the meager width of the lines of mortar.

The *Liber Pontificalis* states that Pope Gregorio IV (827–844), during his pontificate, other than enriching the church with gifts, realized important works which include not only the reconstruction of the apse from the foundations and of the sacristy, but also the elevation of a «porticus quos etiam . . . variis ornavit picturis» (Duchesne 1892, II: 79–80; 83).[6] The word «porticus», in this passage, has led to different and conflicting interpretations. Krautheimer refers this passage to the total erection of the side aisles in addition to their decoration with frescos (Krautheimer 1971, vol. 1, 245; 262). Therefore while Krautheimer thinks that Gregorio IV had rebuilt the church «su scala più vasta», other historians as Giannettini and Venanzi, who have written a monograph on the church (Giannettini and Venanzi 1967, 19–20; 34–35) and who also agree upon the realization of the side aisles, don't think that this operation has concluded the total remaking of the church. Muñoz (Muñoz 1926, 14), instead, attributes the passage from the *Liber Pontificalis* to the construction of decorated porticos with the paintings all around the church.

To this phase of reconstruction probably we must attribute the side extremeties of the front, still visible, since the structures have been fully preserved under the plaster, Figure 8–C. This survey has, in fact,

highlighted, at about 4.20 mt from both of the actual door-posts, the combination of two different building structures assignable to the realization of the side aisles, as can be read in the biography of Pope Gregorio IV. The masonry is constituted by a brick curtain that presents irregularity in the brick line and in the same not suddenly surface of the walls. The brick form (5 recurrences) has a dimension of about 26–29 cm; in addition to the height of the bricks, rather diversified, —between 2.5 and 5 cm— the length also shows different dimensions —from 9 to about 35 cm. The mortar, a greyish white color and without a finishing touch, has a height varying between 1.5 and 3 cm.

In the following periods, or rather until the end of the XIIth century, no significant interventions were realized on the front, but only near the Arch of the Argentari, Figure 8–D, where the masonry has an irregular course typical of the medieval period. The XIIIth century proceeds with not only the construction of the portico, a gift from the prior Stephen Stella as it appears engraved in the lintel, but also the partial change of the front; in fact, the original entry was closed to realize the actual door in the center of the front.

One important document is the Code of san George (1309–1343),[7] Figure 10, where, in a letter head is represented a figure of the church of St. George in Velabrum during the time of pope Zaccaria (741–752): a building with three aisles, three entries and a round window aloft corresponding to the central aisle, still at this time without the portico. In this figure, however, the height of the façade is different and lower than the actual one; it is, in fact, in the XIIIth century, during the construction of the portico, that it come subsequently modified: the actual entry was opened —its portal was realized utilizing Roman marble fragments[8] and the oculo was realized in the front— its frame, Figures 11, now in the leading wall of the left aisle, was also obtained from to pluteus of the IXth century. In the same image shown in the Code, on the portal, an arch is visible, however, this element does not correspond with the present day arch in the front; this arched structure, dated by historians to the XIIIth century, in reality, as we will subsequently see, has been attributed, by the present study, to the elevating of the church front in the XIXth century.

At least two of the restaurations, realizzed in the XIXth century, have, in fact, concerned the upper part of the front; according to the historical documents, the realization of the tympanum was commissioned, in 1825, by Anthony Santelli. Probably, in this period the front must have been made higher as it is also testified by some ancient documents. Also, the plaster in this portion of the front, that simulates bricks (it is treated like brick- «finta cortina»), is also attributable to this phase and precisely to the pontificate of Gregorio XVI (1831–1846). The plaster that simulates bricks, required by the rough building materials, was spread on brick structures. In this same period, the circular opening of the front was deprived of its original marble frame which was exposed inside the church.

Figure 10
Image of the church from the Code of san George (1309–1343), in a letter head is represented a figure of the church during the time of pope Zaccaria (741–752) (Muñoz 1926, pl. X)

Of interest is the building curtain located in the upper part of the front —above the entrance door to

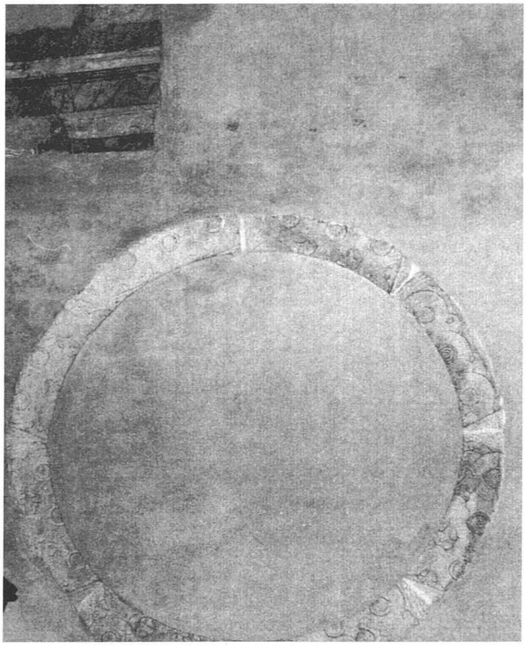

Figure 11
Marble frame of the oculo in façade, now in the leading wall of the left aisle (Author's photo)

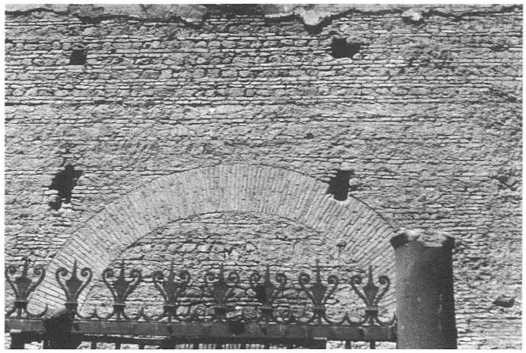

Figure 12
Image of the church, particularly the round arch (Author's photo) above the entry (author's photo)

the tympanum— characterized by the succession of hewn tuff and two brick lines, Figure 12; this masonry is dated back by historians to the VIIth or maximum to the XIIIth century, but is really to be attributed to the elevation of the front in the XIXth century.

The direct analysis of the masonries, this survey and the documentation from public records, have, in fact, together revealed that the whole portion of the front with striped masonry had been totally reconstructed in the years 1823–1829, according to a project subsidized by the «Adunanza of S. Maria del Pianto» which, with the pontifical Bull (11 July 1823) of Pious VII (1800–1823) was granted to the basilica of St. George in Velabrum. The Pope, in fact, on that occasion, authorized the reparation of the roofs and the reconstruction of the falling façade; these works, however, were to be completed only during the pontificated of Leo XIII (1823–1829).[9]

The possibility to examine directly the masonry that had always been hidden from the plaster has finally furnished accurate data on the historical and construction phases of the upper part of the front and of the two archs in the entry, Figure 13, attributed by current historiography to the interventions undertaken between the XIIth and XIIIth centuries.

The round arch on the door has been, Figure 12, in fact, always unanimously dated to the XIIth century for its building characteristics: the arched lintel realized with whole bricks, its height and regularity without sfrayng have always been referred to a past period in the height of the Middle Ages. The arch close near the frame of the door, Figure 13, realized with partly whole and partly fragmented bricks to regularize the extrados of it, has been, instead, attributed to the beginning of the XIIIth century; also

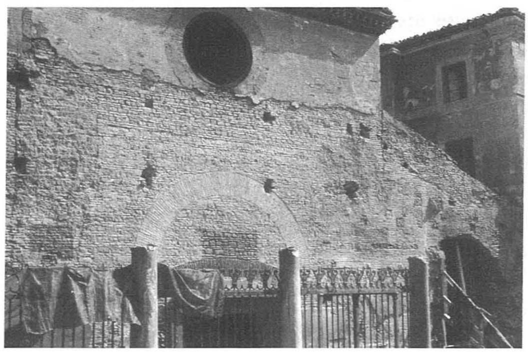

Figure 13
The two archs above the entry (Author's photo)

the striped masonry, between these archs, has often been compared with similar Roman examples, as the remaking of St. Clemente in the XIIth century.

Krautheimer (Krautheimer 1971, vol. 1, 247) exclusively includes the upper part of the roof of the portico to the interventions of XIXth century; Giannettini and Venanzi (Giannettini and Venanzi 1967, 47–48; 73) identify the striped masonry located above the door as structures of the VIIth or maximum of the XIIth century, dating attributed to comparisons made with other roman churches.

Besides the visual investigation of the masonry between the two archs and the extreme sides of the portico, that have already during this survey shown a technique and a workmanship different from that which characterizes other roman churches between the XIIth and XIIIth century, both a document, preserved in the Historical Archives of the Vicariato, and some chronicles of that time have been determinant for a new dating that attest that works were undertaken in August 1823 (*Diario di Roma* 1823, 96: 6–7).[10] These works involve, not only the rebuilding of the front, but also its elevation with a tympanum over the roof of the central aisle. The works were partly financed by the «Adunanza of S. Maria del Pianto» that had asked the pontiff Leo XII (1823–1829) for economic aid to undertake the works in the church which had gone to ruin; the situation appeared rather serious, in fact the roof was completely devastated and the front appeared already «fuori equilibrio di un palmo e mezzo; ed il soffitto, ed i tetti, ed il pavimento avevano necessità di sostegno».[11] The works, realized by the architect Giovanni Azzurri (Rome 1792–Rome 1858), were finished only in march 1824;[12] also on this date the document testifies that the new «travatura» realized was solid and «ben guarnita di staffoni di ferro: il tetto quasi ricoperto in ogni parte». The document continues confirming the realization of the new façade «pressoché del tutto riedificato con due archi in costruzione, e adornato di cornicione, di timpano, e di croce di ferro: il soffitto risarcito, e stabile renduto»; previously, in december 1823, the *Diario di Roma* had recorded the demolition of the front «fino all'architrave di pietra della porta» (*Diario di Roma* 1823, 96: 6–7).

So we have been able to confirm that the whole structure above the entry is due to the works in the years 1823–1824; it is exactly on this occasion that the two archs above the actual entry are realized: the arch above the door, Figure 13, is manufactured with bricks of different dimensions but of the same color; some bricks, 40 cm long, are alternated in a discontinuous manner with others, fragmented or whole, but sets of head (12 cm around) that they define a uniform line extrados. The same regularity of extrados, Figure 12, characterize also the upper round arch composed by bricks 60 cm long alternated with others, of the same red-yellow color, but sets, within the height of the arch and with a recurrent rhythm, two of head (12–14 cm around) and one in the center back (25–30 cm around). Further more, while the bricks of the arch above the door are divided each other by thickness of mortar, those of the round arch have some very thin layers.

While to the right the two arches are connected to the ancient masonry of the VIth century, to left and in the building portion between them they are connected to a striped masonry, it also attributable to the nineteenth-century works, composed of alternate lines of blocks of tuff (from 1 to 2 lines) and bricks (from 2 to 3 lines), connected with light grey mortar with yellow elements.

In the façade we find, therefore, three different masonry: the brick work (VIth-IXth century), the striped work (XIXth century) and another masonry with little tuff blocks aloft left near the bell tower, at 5.40 mt from the actual pavement of the portico; this last masonry, not easy to date, is composed of pyramidal tufelli (little blocks of tuff) with the greatest base in the façade and the sides tilted to 45° on a horizontal plan. This masonry identifies a limited area with only 5 lines of tufelli —around 1.40 mt of length × 0.50 mt of height— placed in a rather irregularing connected manner, with the same disorder, to lines of bricks and lines of parallelepiped blocks of tuff. The building masonry realized with blocks of tuff appears rather rough and with horizontal layers of clear grey mortar with big elements. All this portion near the bell tower, of a rectangular dimension —3.20 mt of height × 1.80 mt of width— characterized by a different and a slightly regular building masonry, has, during the survey phase, posed both great interest as well as doubts and perplexity. As is visible today, the interventions during the centuries, aimed at harmonizing and integrating the different parts of the complex, have, in fact, made difficult the recognition of the different building masonry phases. Yet

uncertainties on the probable dating of such masonry have been immediately removed due to the documents of the archives that testify demolition works during the nineteenth-century: the demolition of the crumbling front and the definition of the actual prospect, the recovery of ancient marble elements inserted in the ancient front: two marble railings and two small columns; an inventory, dated to 1824, so describes the church: «Nel fondo della navata destra quando si entra ossia a cornu evangelii si veggono due colonnette di marmo bianco, con capitelli gotici antichi, e base e pilastro di stucco trovate nella riedificazione della facciata fatta l'anno 1923 . . . Al lato delle due colonnette nel muro della stessa navata sono incassate nel med[esim]o muro poco alte dal pavimento due antichissime cancellate di marmo che erano sepolte l'una sopra la porta grande della Chiesa, e l'altra verso l'arco degli Argentieri, e fra l'una e l'altra si ergevano a parapetto le due colonne di cui si è già parlato non scorgendosene all'esterno contrasegno alcuno».[13] Evidently the present day tamponades, now in the front near the bell tower, were built on this occasion to fill the empty space obtained from the moving of the marble fragments.

The discovery of the marble railings and the small columns in the masonry would confirm the hypothesis that the front of the church has absorbed a civil roman house or a diaconate, antecedents of the foundation of the church.

The same document records the discovery of the marble frame of the round window in the front, that was be arranged in the left aisle: «nel prospetto della navata sinistra, ossia a cornu epistolae evvi un gran circolo di marmo intagliato gotico barbaro, che forse anticamente aveva un altro uso: in quest'ultima rinnovazione della facciata rinvenuto per stipite circolare della finestra sul tetto del portico; situato però in guisa che la superficie piana era nell'esterno, e l'intaglio sepolto trovasi nel muro: onde nella calce interiore trovasi l'impressione dell'intaglio . . . Vi si veggono ancora varie parti di musaico ritrovate nella demolizione dell'antica facciata che la rozza ignoranza dei muratori avea dissipati siccome oggetti di niun conto». The writer of the inventory realized that the frame reimployed for the round window originally had another destination; in fact, the element presented sculptural decorations in the interior part, closed in the masonry, that with its new use, didn't make sense be left in sight anymore.

Therefore, in the early years of the XIXth century, the façade reached its definitive appearance; precisely in this phase, in order to conclude the works of the elevation, the iron cross, present even today, was put up with «base di travertino intagliata: cornicione gotico e timpano con lastre di lavagnone . . . il tutto fatto di nuovo nel restauro del corrente anno 1824».[14] On this same occasion, with the elevation of the façade, the triangular pediment was also realizzed, Figure 14; this structure took on same element known as «wolf teeth» that characterizes the frame of the

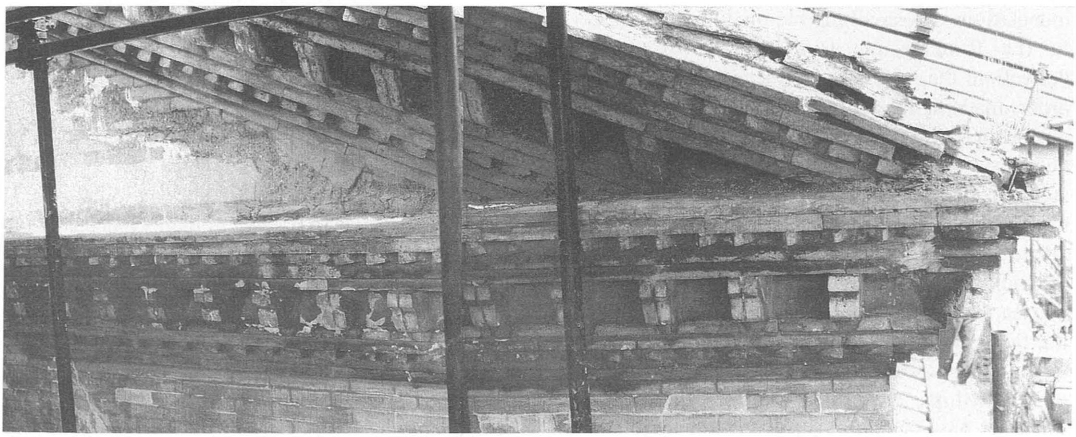

Figure 14
The big eardrum realized in XIX century (Author's photo)

medieval portico. The masonry materials inside the tympanum, realized during the works conducted by the architect Azzurri, is constituted in sum by a wall curtain set in work with whole fragmented bricks, covered with plaster that imitates bricks —«finta cortina»— required by the rough work of the masonry. The form of five lines is set on a dimension of 25 cm; the masonry is built using long tiles from 20 to 27 cm and around 4 cm thick. The mortar is a clear grey color with brown pale yellow and red yellow components. The tympanum is, instead, made of rather long whole yellow bricks —around 30 cm—; the bricks are around 4 cm thick and with a mortar coat of a rather thin, clear, grey color.

The plaster that imitates brick-work, above the portico, was chosen in order to dignify the little refined masonry; for this reason a plaster protection that simulates lines of bricks was preferred —5–6 cm of thickness, 35 cm of length and 17 cm of width— alternating in head and list, stagered among themselves and linked according to a scheme defined from the handbook, «gothic». The choice of the «gothic» sizing wants to intentionally suggest a technique, even if simulated, similar, at least in «type», to that of the portico and of the bell tower.

The bell tower, Figures 15–16, built partly on the Arch of the Argentaris and partly on the first span of the left side aisle, owes its structure to the XIIth-XIIIth century, even if the top tiers could be attributed to an earlier period.[15] The bell tower, with its irregular base, is divided into plains by dividing frames constituted from brick lines alternated to fillets with indentations and small marble modillions, Figure 15. In the Romanesque style of lombardy region derivation, the tower is developed in height on four orders made light by three-mullioned windows that in the last tier are opened like a loggia. The bell cell has, on every side, a three-mullioned window whose small archs, with double arched lintel, are sustained by mullions with capitals like a «clothes hanger». Alberto Serafini (Serafini 1927, 167–69) identifies the mullions of the bell cell as «spolia», as almost all the marble corbels inserted in the frames that divide the floors of the tower. The mullions introduce, not only a different material, but also diameters, workmanships and dissimilar treatments; some mullions have smooth shafts others, instead, show grooves in the entire height, others also show a stumpy rudentatura in the inferior part. Contrarily the

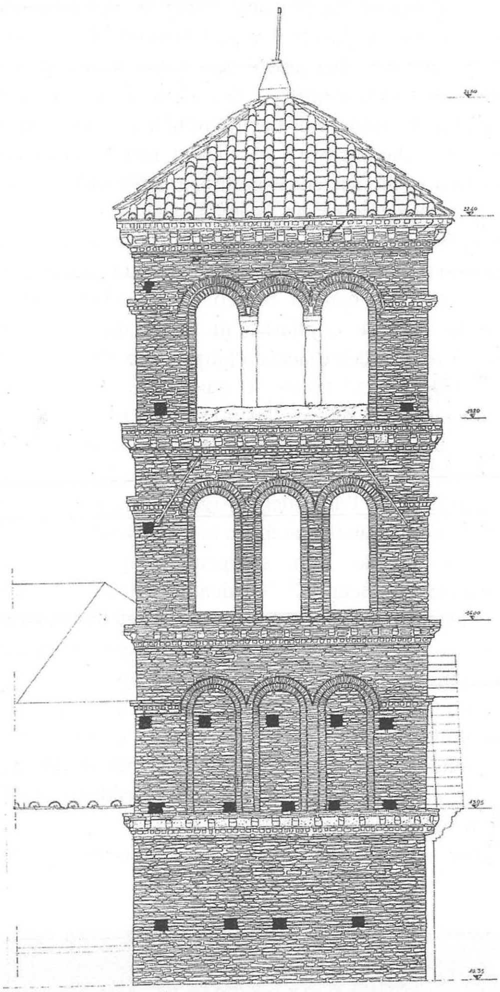

Figure 15
The bell tower-north (Author's survey)

big capitals which looks like «clothes hanger» seem to have been realized inst for this occasion: they have a conformation of «flattened sides» that Serafini likens to the type of St. Rufina and St. Cecilia in Rome (Serafini 1927, 168).

The inferior tier of the tower has only decorative blind arcades sustained by brick pillars. On the front of the church, in the lower zone, a blind three-mullioned window on pillars appears that doesn't have any correspondence in the other three sides of

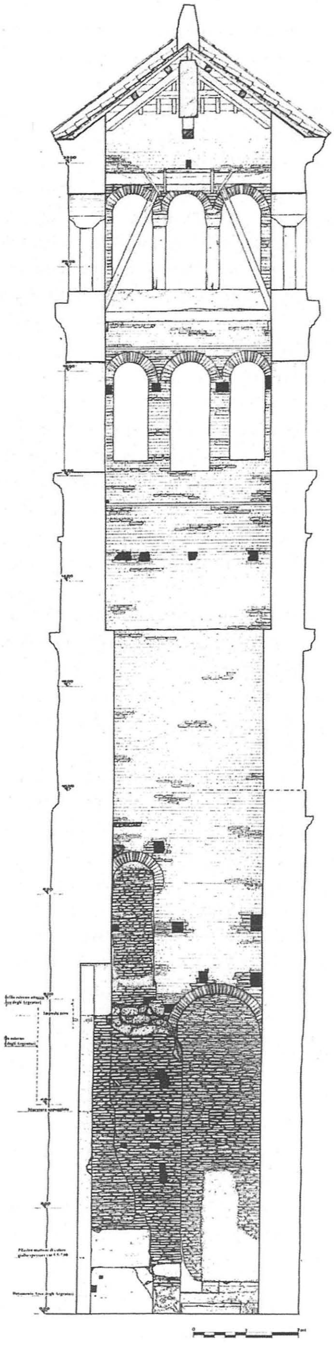

Figure 16
The bell tower inside-north (Author's survey)

the tower; this three-mullioned window differentiates from the others due to its simple arched lintels with only one archivolt adorned on the top with a simple frame of small brick fragments that also characterizes the superior three-mullioned windows, however, with a double bricks arched lintel. Besides, there don't exist any ornamental elements that horizontally tie the other openings, even if they too are closed. A thin decoration of bricks, in fact, accompanies in the upper rows the bending of the small archs and it continues horizontally on the four sides of the tower.

In the basis of the study of the masonry typologies we have been able to individualize, also for the bell tower, an alternation of building phases of at least three separate periods. In fact some differences are evident in plan and in volume, as well as considerable differences on its levels. Such construction characteristics derive from the need to adapt different and chronologically tied projects.

The first structure of the bell tower is referable to the intervention of Gregorio IV in the phase of amplification of the preceding building of Leo III; these works centered around the south and west sides of the tower that in the IXth century delimited part of the building front and of the left aisle of the church. Between XIIth-XIIIth century, the real bell tower was built set up directly on the Arch of the Argentaris and on the first span of the left side aisle that was closed due to its with inside a column.

The upper building conformation, especially in the last tier, could be attributed to a different moment from the primary resolution, as some sixteenth century prints testify, even if currently we have not found difference in materials and workmanship.

As it appears, on the ground of the reflections exposed until here, the existence of pre-existent structures has favoured, but at the same time bound, the construction of the church.

This study has wanted, therefore, to understand many enigmatic construction aspects of the building, but above all to arrive to the formulation of chronological and interpretative hypothesis sustained by a greater evidence of facts, through the direct, architectural and archaeological investigation, operations aimed at specifing the meaningful points of the complex and its relationships with the pre-existing structures.

Notes

I want to thank the managers of the works that have kindly allowed me to introduce this study that derives from the charge received from the Office for the Cultural and Environmental Property-Superintendence for the Environmental and Architectural Property in Rome, for the survey, the graphic elaboration and the historical-documentary research on the church of St. George in Velabrum (Rome).

The present article on the masonries of St. George in Velabrum probes part of a study published in the *Bollettino d'Arte*, Ministero per i Beni e le Attività Culturali, special number, 2002.

1. The planning and the direction of the restauration have been coordinated by the architects of the Office for the Property and for the Cultural Activities-Superintendence for the Environmental and Architectural Property in Rome: Laura Cherubini, Maria Constanza Pierdominici and Pier Luigi Porzio.
2. The disjunction of the plaster on the front, in fact, has point out the building structures allowing to probe the study of it.
3. Antonio Muñoz (Rome 1884–1960) took care of the restauration of St. George in Velabrum as Superintendent to the Monuments of Rome and the Lazio; in the same years he undertook other works: the isolation of the Temple of the Fortuna Virile in the Foro Boario and restaurations in St. Prassede and St. Balbina. From 1929 he worked for the Governatorato in Rome as manager of the Division Antiquity and Belle Arti.
4. The church of St. George in Velabrum is built probably on a pre-existing diaconate used as a storehouse or a laic roman building, transformed later in the church. The use of «spolia» supports the presence of buildings predisposed already for the use, rather than specific ornamental pleasure. The poor quality of some of the building masonry, in fact, justifies not only on the general level, rather low, of the contemporary skilled workers, but also in the «poor» use of the diaconates, that imposed economical works for the urgency of the preparation.
5. From the biography of pope Leo II (682–683), in the *Liber Pontificalis*, the following is noted: «huius almi pontificis iussus aecclesiam iuxta velum aureum in honore beati Sebastiani edificata est nec non in honore martiris Georgii» (Duchesne 1892, I: 360).
6. «Fecit autem in ecclesia beati Christi martyris Georgii . . . hinc inde porticus quos etiam. . .variis ornavit picturis. Absidam vero eiusdem diaconie a fundamentis . . . cum summo studio composit . . . quod eiusdem venerabilis diaconiae secretarium prae nimia temporum vetustate marcesceret, noviter pro ipsius amore sec gratia allorum ad meliorem erexit honorem. Obtulit itaque sanctissimus papa ubi sopra haec dona: vestem de fundato una cum Cristo clabro habentem imaginem Salvatoris et martyrum Sebastiani atque Georgii . . . fecit autem in confessionem rugas de argento» (Duchesne 1892, II: 79–80; 83).
7. The Code of san George, manuscript of the cardinal Stefaneschi realized in Avignone where he follows the papal court, is decorated with miniatures attributed to Simone Martini or one student of his.
8. Door-post and lintel are arranged with big fragments of trabeation, decorated with leaves, derives, evidently, from roman buildings.
9. Archivio Storico del Vicariato (AV), Pia Adunanza di S. Maria del Pianto, b. 485.
10. AV, Pia Adunanza di S. Maria del Pianto, b. 485. In the *Diario di Roma*, 3 december 1823, the church is so described: «Era in grave pericolo di rovinare la famosa basilica di S. Giorgio In Velabro, se per la vigilanza dei Direttori dell'adunanza de'giovani di S. Maria del Piano non fosse stato in tempo scoperto il danno, e con grave dispendio riparate. Quattro incavallature del tetto di palmi 46 di lunghezza erano per cadere, la prima per essere sgavezzata nel mezzo, e le altre tre come fradice nelle teste. Non fu questo il solo danno prodotto dall'abbandono in cui trovassi codesto tempio per circa 20 anni: tutti gli staffoni di ferro appartenenti alle passine della navata media furono allora derubate, onde i paradossi senza ritegno alcuno . . . le fradice intacche delle corde facevano temere ad ogni momento la distruzione del tetto intero. Trovassi inoltre riempito di calcinaccio e di altre materie estranee il muro della facciata, ed inclinato verso la parete esterna di once 18 circa: esso è stato demolito fino all'architrave di pietra della porta, ed innalzato nuovamente con due archi in costruzione. Ora si adorna di timpano con cornicione gotico corrispondente, e croce di ferro. Il lavoro si eseguisce sotto la direzione del sig. Giovanni Azzurri romano ingegnere pe' lavori di fabbriche camerale. Nella demolizione della facciata si sono trovate due ferrate di marmo antichissime, due colonnette con capitelli di marmo ed alcuni frammenti di musaico» (*Diario di Roma*, 1823, 96: 6–7).
11. The «Adunanza of S. Maria del Pianto' receives from the pope 350 scudi of 1000 scudi asked in the memorial.
12. Giovanni Azzurri was born in Rome in 1792; he, student of Raffaele Stern, has been one of the exponent of the roman Neo-Classicism. He was a teacher in the roman Academy of Beautiful Arts. Your works are: the Casino of the Wood Parrasio on the slopes of the Gianicolo in Rome, buildings Galitzin

and Guglielmi in Civitavecchia (near Rome); besides he restored the barberiniano mosaic of Palestrina (near Rome).

13. AV, Pia Adunanza di S. Maria del Pianto, Inventario, b. 485.
14. *Ibidem.*
15. The following extracts are the opinions of different historians; they agree on the bell tower structures of the XII-XIII century. «L'uso della stilatura scompare nella seconda metà del XII secolo . . . Il campanile nelle mura visibili presenta la stilatura» (Muñoz 1926, 37; 42). «La sua muratura [del campanile] è simile a quella impiegata nel portico, benché questo, essendo chiaramente addossato al campanile, sia di data posteriore. Ad ogni modo, sia il campanile, che sembra del secolo XIII, che il portico sono di data posteriore al corpo principale della chiesa» (Krautheimer 1971, vol. 1, 247). «Il campanile presenta nelle murature visibili della parte inferiore la stilatura dei letti di malta . . . l'uso della stilatura ci dà la certezza che il campanile fu costruito non ai primi del XIII secolo . . . ma nel corso del XII, dato che già dalla fine del XII secolo questa tecnica . . . non è più usata» (Giannettini and Venanzi 1967, 48).

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Learning from traditional vaulted systems for the contemporary design. An updated reuse of flat vaults: Analysis of structural performance and recent safety requirements

Giuseppina R. Uva

The Boveda plana is a particular solution for covering a quadrangular area that can be seen as a spatial vault in which the curvature tends to zero. The static behaviour is essentially based upon the connection among the different ashlars in the space, distributing the load in both the direction of the floor. The horizontal thrusts are very strong, and the solidity of the whole masonry is guaranteed only if horizontal displacements are prevented. Otherwise, the collapse shows all the features of brittle ruptures.

The aim of this research work is to develop a system for the horizontal structures made from a set of dry-assembled blocks. If we want to propose a contemporary structural system that is borrowed from these historical examples, it is important to overcome the outlined drawbacks. The work is focused over the following aspects:

- Analysis of the structural behaviour of the system. There is a serious difficulty in modeling structures that are naturally discontinuous. The ancient knowledge of blocky structures has been abandoned for a long time, and now very few methods of computation exist for discrete systems. Rigorous approaches are time consuming and computationally expensive. Equivalent continuous model are a rough approximation of the reality. Different possibilities will be explored and tested on the case study, with a particular reference to the use of Finite Elements with proper adjustment for the particular case.
- Updating of the system in order to prevent a brittle collapse, to endow the structure with a certain degree of ductility (that is nowadays a fundamental law requirement). Reinforcement bars have been introduced, and the shape of the blocks has been accordingly designed. Formal and structural evolution of the system is examined.
- Analysis of two possible solutions for the cables (pretensioned or loosen), considering the question of the installation procedures: direct assembly in the yard or pre-assembly and pretensioning of the whole slab, that is later positioned over the supports by using a crane.
- Use of alternative materials such as reconstructed stone, brickwork, and synthetic resins in order to optimise the weights and the structural performance. The spin-off on formal design of ashlars will be analysed.
- Problem of the structural joints, with an attention to the box behaviour of the building and to the elimination of the horizontal thrusts.
- Testing on scale models of the flat vault, showing some qualitative characteristics of the structural response.

Introduction

This work is part of a wider research project carried out within the Faculty of Architecture of the Polytechnics of Bari, concerning the analysis and updating of traditional stone architecture, in view of an alternative, contemporary design within the Mediterranean area.

The research group has been recently developing a work on this subject, thanks to the «Young Researchers Grant». This project is aimed at the reuse of traditional arched and vaulted system (dry stone blocks) in historical contexts. The synthesis between modern exigencies and a sustainability of building actions is realized, according to us, through the updated use of traditional techniques. Rehabilitation, in this sense, means continuity of types, materials, structural conception. Of course, it is necessary to study ancient examples from an historical and geometrical perspective, and afterwards to use structural tools of analysis in order to verify the static performance of the elements according to the different texture, and to design new proposals.

One of the case study on which the group has been focusing the attention is the Spanish boveda plana, of which the historical development has been faced [1–5] and the existing example of the *Casa de Mina de Limpia* near the dam of Ponton de la Oliva has been surveyed and analysed [5]. The study consists of two phases: historical and typological analysis; drawing, modeling and structural comprehension of the investigated elements. On the basis of the results, the design of prototypes to be used in the reconstruction of historical elements is performed (the application is the reconstructive hypothesis for the *Casa del Guarda* flat-vault).

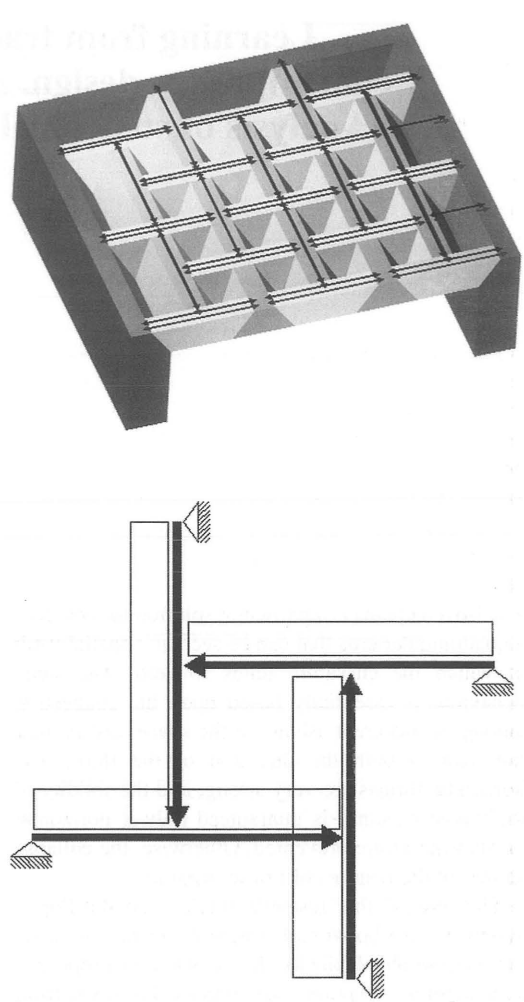

Figure 1
Schematic arrangement of the flat vault according to the early solution of Abeille

The *Boveda Plana:* solutions in the theoretical studies and existing examples

The *Boveda plana* is a particular solution for covering a quadrangular area, and in spite of its planar configuration, is more similar to a spatial vault in which the curvature tends to zero. The static behaviour is then significantly based on the three-dimensional interlocking of the blocks, that establishes a three-dimensional lattice distributing the load on the supports, using a configuration that could be derived from the platband (fig. 1).

Many different geometric solutions are possible for the block shape, as the investigations performed over historical treatises have shown. The development of different solution is characterized by an increasing complexity in the cutting and, accordingly, in the structural performance.

In some cases, the reaction is lumped in particular points on the supporting walls, like in the early elaboration of *Abeille* ([1, 4], fig. 1).

In other examples, a continuous distribution is achieved, in accordance with the complexity of the blocks' shape. It is worth noting that this last situation is reached for the more advanced and complex solutions. This is the case, for example, of the Truchet solution [1, 4], in which the ashlars are cut following quadric surfaces. It can be considered the most refined evolution of the system of the flat vault, both in the geometrical complexity and in the improvement of the static performance. Indeed, no practical implementation has ever been realized, or at least it hasn't been discovered yet. Maybe now, at the end of a process of re-interpretation and reformation of this architectural system, it could be possible to make the proposal feasible. It is in fact necessary to make easy and serialized the cut of the pieces, also in the perspective of providing the system with proper steel reinforcements. The modern technologies of cad-cam will help us in this task, supporting the design.

In the system of the boveda plana, the horizontal thrusts over the supporting elements are strong, and the stiffness and solidity of the whole masonry is guaranteed only if every horizontal displacement is prevented. If the masonry panels are rigid enough and well scarfed to form the masonry box, the floor is very stiff. Otherwise, the collapse of the structure is sudden and unexpected, showing all the features of brittle ruptures: neither warning signs nor large deformations arise, and a snapping collapse takes place. Once the sliding over the contact surfaces of the blocks are activated and the hooping action of the walls is no more able to contrast them, the structure cannot find an equilibrated configuration. It is evident that in these cases very high safety factors are required.

Since the aim is to propose a contemporary structural system that is borrowed from these historical examples, it is important to overcome this drawback.

Historical masonry structures: modern interpretation of the structural behaviour

From a methodological standpoint, a preliminary historical characterization of the architecture, the materials and the structural elements is very important, and do assume a central position within the structural analysis. By integrating these instruments of knowledge with more advanced numerical and modelling tools, it could be possible to obtain a Contemporary approach to the Design and the intervention on historical building, that does not break with the past, but rather assimilate the tradition.

The analysis of the historical elements and the proposal of updated elaborations have been guided by the idea that the texture (that represents often the decorative pattern) is a central point in the design with structural stone, and could be advantageously exploited in order to improve and optimise the structural response.

The case study of the Ponton de la Oliva

The first part of the research work as been devoted to the study of the historical examples as they were described in the treaties of stereotomy of the Seventeenth century, and in the survey and analysis of one of the few existing examples of flat vaults: the little service building near the Dam on the Lozoya River, at the Ponton the la Oliva.

The building yard of the Dam and the outlying service buildings represented an experimental and scientific «laboratory» of construction. The designers were actually scholars of stereothomy, and taught in this subject at the University of Madrid. The stone masonry building technique was very advanced and refined in Spain, as witnessed by the high level achieved in the studies on stone cutting in the seventeenth century (formalized in the historical treaties). This well-established and long tradition is an important element in the analysis and comprehension of this unique example of hydraulic plant, in which *out-of-plane* loaded masonry is masterly used, experimenting daring technical solutions for dry cut stone masonry. In the dam, the sophisticated texture of the blocks, designed according to severe stereothomical rules of cutting that can be recognized in the historical treaties, introduce an important improvement in the mere gravity/frictional mechanism. The use of the dovetail joint improves the interlocking of the blocks, enhancing the strength to the mutual sliding and to the rotation induced by the overturning pressure. The structural performance is strategically committed to the texture of the wall. The conveyance of the water pressure to the abutments is

so achieved through the combination of two mechanisms: the classical gravity reaction and the frictional interlocking among the blocks establishing a spatial platband-behaviour similar to that of the Boveda Plana explained in the book of *Frezier* [1].

Indeed, the structural problem to solve was the same: the loads act in the direction perpendicular to the «plate» (out of plane actions), and have to be absorbed —and then conveyed to the restraints— by means of a plane structure made up by no-tension materials and relying only, if conventional solutions are adopted, on the development of the friction reactions. The closeness of the two structures seems to be validated by the presence of the little space, intended for containing the technical equipment, located nearby the dam wall and covered with a Boveda Plana (fig. 2–indeed, this is one of the few examples of flat vaults ever realized). Maybe, it was a *divertissement* of the designers who wanted to apply the theoretical solutions described in the treaties, and the presence of a yard specialized in stone cutting made it possible the implementation of extremely complex geometric configurations. Certainly, they had to solve a tricky problem for the dam construction, and used all the tools and knowledge available at that time. The little and fascinating Boveda Plana witnesses the high level reached in the building techniques, and the care for details in order to guarantee a well-done construction.

Figure 2
The flat vault of the Casa de Mina de Limpia near the dam of Ponton de la Oliva

The role of stone blocks' shape in the structural performance

For the B*oveda Plana*, the mechanism of the work can be schematised through the simple system shown in figure 3 (beams organized in a celtic fashion arrangement). Each of the four beams has one perfect constraint on one side and is elastically constrained on the other by the following one, and is then loaded by the previous.

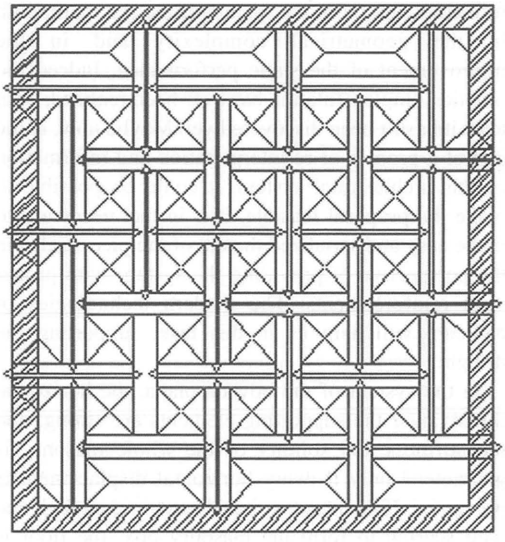

Figure 3
The spatial platband scheme of the boveda plana

It is so possible to span a fixed length using shorter elements, but uniformly distributing the weights as well on the restraints. A sort of circular diffusion of the load is generated, where each element is loaded and loads the other to the same extent. This distribution, for the flat vault, involves both vertical and horizontal actions, determining the overturning thrusts on the supports (fig. 4). Each block exerts a thrust that is, on a first approximation, perpendicular to the contact surface.

Revision of the constructive system of the flat vault according to contemporary structural needs and ductility requirements

While re-proposing stone as building material, and developing a system for the horizontal structures

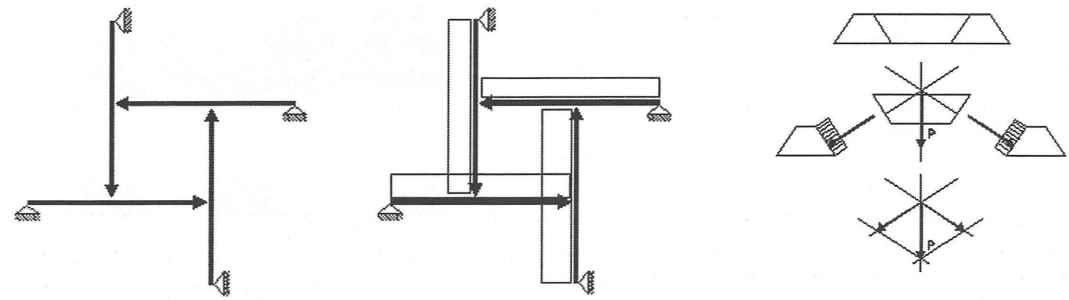

Figure 4
The constraint scheme for the spatial equilibrium and thrusts distribution

made from a set of stone or stone-like blocks dry-assembled, it is necessary to justify them in terms of feasibility and convenience.

Besides the static safety, it is then important to guarantee functionality, economic convenience, and standardisation of the building process (in particular by focusing on quality). Speaking about structural stone, it is evident that costs regarding materials become relevant, in particular with regards to characteristic thickness of these structures. Secondarily, the cutting of stone needs high skilled hand workers, and this could be an unsustainable making a common and wide use of stone practically impossible.

In this paper, the question is faced with a particular reference to the case study of Ponton de la Oliva, and to the proposal of the reconstruction of the *Casa del Guarda* flat-vault (for further details on the formal, typological, and constructive elements of the blocks and of the system see [3]).

The first aspect to be examined is the prevention of brittle collapse. Not only it is necessary to provide a sufficient margin of safety with respect to collapse, but also a control on the modality of the collapse itself is required. The structure should be endowed in fact with a certain degree of ductility (that is nowadays a fundamental law requirement), a sort of an emergency supply that, in case of a failure, averts devastating effects.

This idea is well established in the field of r.c. and steel constructions, and for masonry buildings is a more delicate question.

It is wrongly believed that masonry is not able to develop any ductility. The experience as shown, instead, that a well designed and executed building can have an excellent behaviour even under unexpected and strong stresses (like during seismic events), and perform a good ductility and hysteretic dissipation. An essential premise is that a good connection is realized among the different supporting elements, both horizontal and vertical.

In this way, a box-like behaviour is induced, and a beneficial effect is recalled: the shear resistance of those panels positioned in the most favourable direction is recalled.

In accordance to these principles, after studying the flat vaults in their historical and formal evolution (pointing out the interesting static and expressive possibilities), different updated solutions have been elaborated, in view of a rational contemporary proposal.

To improve the system (in the sense that has been just precised), the use of reinforcement bars is foreseen, and the shape of the blocks is accordingly designed.

The ties (that could be pretensioned or even loosen) can have three different functions:

— eliminating the horizontal thrusts over the supporting walls that would disarrange the masonry box and cause the overturning —and collapse— of the system;
— supplying the floor toothing to the walls (if the anchoring is brought outside) and providing an horizontal bracing;

— Improve the shear mechanism of mutual contrast (increasing the friction effect, and by a pin-effect);
— Constituting an emergency safety net able to retain the blocks in the case of a sudden and unexpected collapse.

The possibility of developing the above-mentioned phenomena will depend on the particular solution adopted: introduction of the pre-stress; position of the bars with respect to the block. In particular, the position of the bars is related to the technological choice. If a stone cut piece is to be used, grooves on the sides of the blocks should be foreseen. If a prefabricated, reconstructed stone is designed (that could use a resinic binding agent or a cementitious one), the moulding procedure allows the use of built-in holes.

An example is hereafter given (fig. 5), where the reinforcement cables are positioned in the lower part of the blocks (the example in the pictures shows the case of lacunars that are on the extrados of the floor, but it is possible to invert the situation by simply reverting the slope of the faces of the block and turning upside down the system).

In this case, there is the possibility of applying compression prestress through the ties in the lower part of the section. In this way there is a direct action that compensates the effect of the vertical loads. Of course, there is a formal problem in the management

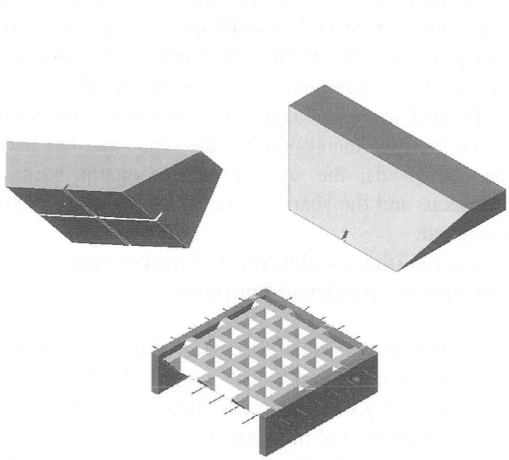

Figure 5
Reinforcement placed at the intrados of the floor

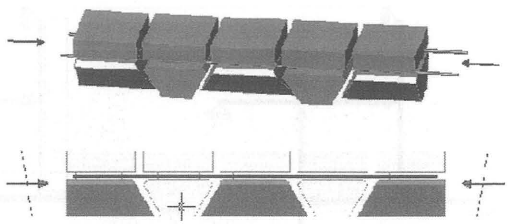

Figure 6
Application of a prestress through ties incorporated into the floor

of the cables, positioned in groves that are visible on the ceiling, even if they are sealed with mortar.

The choice of a system that is cast from artificial stone would completely solve the problem, by shifting the bars in the interior of the block, and allowing the centring of the contrast plates with respect to the section (fig. 7).

The question is then to evaluate the contribute of the introduction of reinforcements into the system. If the cables are not pretensioned, the only function would be that of tying the system and eliminating the overturning thrust. The same result, however, could be as well achieved by placing ties only in the outer walls. However, a safety function in retaining the blocks during the collapse is played, and a small contribution to the shear transmission of the forces is provided by a pinning effect. Much more relevant is the global effect if a prestress is applied (fig. 6). Infact, under this hypothesis, it can be shown that the load-bearing capacity is improved, thanks to the increasing of the frictional resistance on the contact surfaces. This also contributes to raise the energy dissipation in case of limit situations, enhancing the plastic resources of the system.

Another solution is presented in picture 8, in which, even without cutting the hole within the block, it is possible to lower the ties as much as possible. So the elements can be more easily realized in stone too, taking advantage of the prestress benefits nand preserving the integrity —and decorative pattern— of the ceiling.

In this brief exposure of solutions for a contemporary use of the system of the flat vault (the occasion could be the reconstruction hypothesis in the historical context of the Ponton de la Oliva), only the

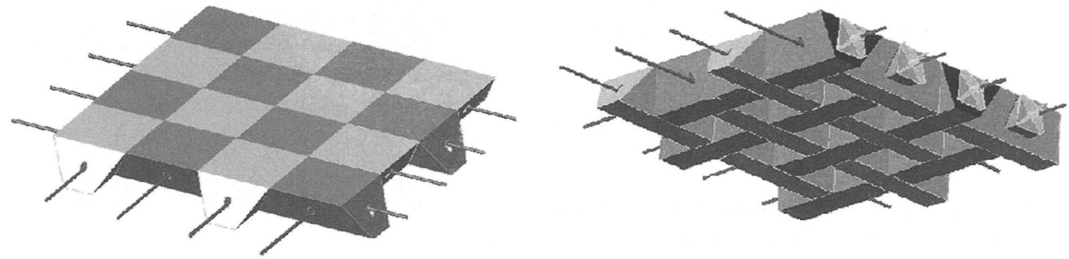

Figure 7
Reinforcement placed at the center of the section

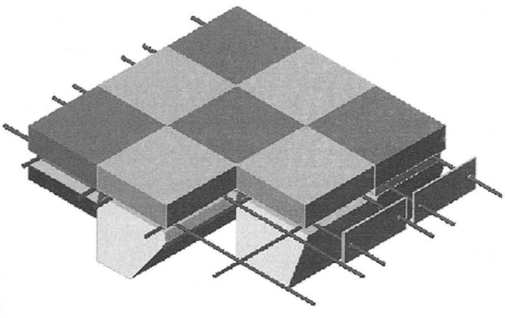

Figure 8
A solution suitable for stone cutting, with quasi-centered ties

geometrically simplest case have been shown, that have allowed an easier positioning of the reinforcements and comprehension of the possible effects attained.

Acknowledgements

This research is being developed thanks to the financial support of Young Researcher Grant. Particular thanks are due to Professor Claudio D'Amato Guerrieri, who, as a coordinator of this research line activity within the School of Architecture of Bari, has been a constant reference; Professor Mauro Mezzina and Calogero Dentamaro, for the precious suggestions and guidelines.

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Historic carpentry in Rome

Simona Valeriani

Some results of a study conducted over the last three years in the framework of the project called «Indagini dendrocronologiche in chiese paleocristiane di Roma»[1] are presented here. The investigation was developed on several levels, with three main aims: to develop a master chronology for dendrocronological datings in the Lazio region; to acquire and process new data able to contribute towards investigating the history and architecture of the buildings examined; to study the history and development of roofing structures covering large spans, starting out from the Christian basilicas of Rome.

In the framework of this project, the study presented here is concerned, in particular, with the last two issues, with the intention of acquiring more in-depth knowledge of the technological and construction-related aspects, considered an integral part of the evolution in time of the buildings examined.[2] To this end, an analysis of the various types of roof and of their features (nodes, joints, static functioning) was started, and at the same time, the technical information obtained in this way was related to the other available sources. In addition to the interest in the construction history, there is the interest for the archaeology of architecture and for the history of architecture in its more traditional sense. These were investigated starting from the roof and from the rooms immediately below it, that is to say from a part of the building that is often neglected and frequently difficult to access, but potentially rich in information. Indeed, the fact that it is a hidden part of the building made it easier to tamper with in time, however, paradoxically, if this happens it is more visible here than elsewhere, leaving obvious signs of the diachronic construction features.

Although the lines along which research has been developed up to now in Italy in this framework have shown an interest in the subject of the history of building, they have paid attention mainly to the technological aspect[3] and to the structural aspect (connected with the issues of consolidation).[4] Experiences of a «comprehensive» nature, in which the roof is investigated as a possible source for the history of the building considered as a whole, are rare. The fact that dendrochronology is not very widespread has also led, in many cases, to the lack of a reliable dating method.

Our research study, therefore, has the aim of weaving together the skills typical of different disciplines, starting out from the observation and documentation of the material evidence «preserved» in roofs and in attics. With this approach, the surveying activity is an important part of the investigation. This is because the detailed drawing drafted on site is understood to be the principal tool for finding out about and understanding the subject-matter of the study. In the many cases in which there was no sufficiently accurate survey of the roof structure, this was prepared on a scale of 1:20, paying attention to construction details such as joints, metal

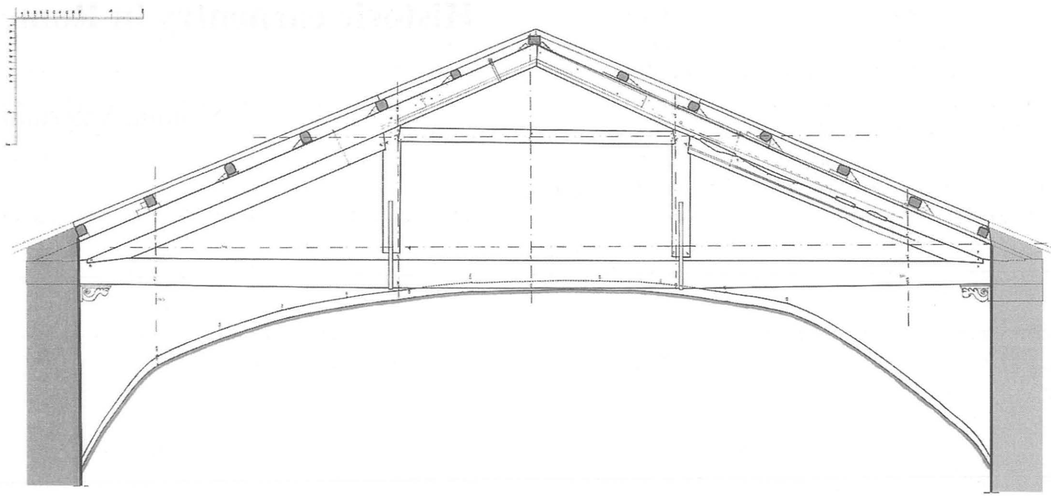

Figure 1
Church of S. Cecilia in Trastevere, Rome. Cross-section of rooftruss (nave) with traces of decorated planks. Survey-drawing, original scale 1:20 (SimonaValeriani)

carpentry and so on, Figure 1. Alongside these, detail drawings (to scales of 1:10, 1:5 and 1:2) were prepared.

The survey was followed by taking systematic note of all the details felt to be significant, such as construction features, traces of working, presence of re-used elements and so on. In this way, plentiful documentation of the building was obtained and the information necessary for proceeding with targeted sampling for dendrochronological analysis was acquired.

Construction material: species of wood and their places of origin

Ever since ancient times, in Italy carpenters have used a number of different species of wood.[5] They had a preference for fir[6] (*Abies alba*), a tree featuring a long, regularly-shaped trunk and lightweight wood, although oak, pine and larch were also widely used. Larch, in particular, was believed to be incombustible, however since it did not grow in central Italy and could not be transported there easily, it could not be used in Rome, where fir and oak were employed.

On analysing those roman historical roofs that have been preserved until the present day, in addition to the species mentioned above, chestnut wood was often found. 79.4% of the samples taken during the course of the study (262 coming from eight different buildings) consisted of chestnut wood, 12.2% were oak and 8.4% were fir.[7] This material therefore influenced to a great extent progress of the dendrochronological investigations carried out during the course of the research project presented here. In spite of its obvious later popularity, it seems that chestnut was not used as construction material until the late Antiquity. It is probable that the custom of growing this plant developed initially in Eastern Europe and in the Middle East,[8] spreading later, in the 5th century BC, to Greece, then shortly afterwards to Spain and to Southern Italy (Fenaroli 1945, 17; Rikli 1943, 359), where it only started to be widely used in Imperial times when, under Tiberius, a marked improvement in the quality of the fruit was achieved.[9] Considered initially only as a food-producing plant, chestnut trees were later employed in manufacturing and eventually in building.

The first evidence of its use in constructions dates back to the end of the 4th century. In a treatise by Palladius Rutilius Taurus Aemilianus[10] chestnut

wood was recommended for open-air structures and for roofs, and was praised for its particular strength, albeit combined with remarkable weight. Oddly enough, this treatise mentions in particularly Spanish chestnut wood, so that one wonders whether this type of wood was perhaps not yet available in Italy or whether material believed to be of better quality came from Spain.

The information resulting from sources in literature is in this case confirmed by material evidence. During the investigation presented here, several chestnut architraves were analysed in S. Stefano Rotondo, the dendrocholological dating of which, confirmed by historic data and stratigraphic considerations, refers back to the 5th century AD.[11]

In the course of the Middle Ages, chestnuts became an essential part of people's diet, and chestnut woods, which until then had not been very extensive, developed rapidly, later undergoing a further significant increase in the 17th century.[12] Alongside the spreading of chestnut trees for food purposes, in time the wood also made a name for itself in the field of building, progressively replacing pine and oak and becoming, in the Middle Ages and in the Modern Age, the most frequently used wood for roofs.[13]

Notes on the use of more than one species in one and the same structure

During the course of the enquiry presented here, it was possible to establish that Roman roof structures consisted not unusually of wood of several different species. This diversity can only rarely be connected with different construction stages. It was often found that the initial construction called for the simultaneous use of more than one material, in spite of the fact that this practice was advised against by writers of treatises (who, however, did not always take an interest in this subject). In this respect, L. B. Alberti went so far as to require the use of wood coming from the same forest: «Et trabes ipsas cognatas esse, hoc est uno materiae genere, unaque silva, una caeli fronte adultas, si fieri potest, eadamque die abscissas oportet, quo paribus naturae viribus par officium gerant» (Alberti [1485] 1966, III, XII, 231). In subsequent centuries, also, the issue was taken up again in treatises in similar terms, for example in the work by Spinelli (1698), who advised against combining the use of both hardwood and softwood.[14] These requirements were justified by the fact that each species of wood has its own physical properties and reacts differently to changes in temperature and moisture, thus facilitating the occurrence of dangerous stresses, in particular in the joints.

On the basis of current knowledge, it is possible to evaluate in detail what the advantages of such a construction practice might be. The different materials, with their respective compressive and tensile strengths, could actually be used in a targeted manner to optimise structures. It appears doubtful, however, that these criteria, which were definitely known starting from the 19th century, with the introduction of modern static calculation methods, could have influenced design even in earlier centuries. In the buildings analysed, it was possible to observe that, where different species of wood that could be traced back to one and the same construction phase had been used, each of them was often used without making any distinction in parts having different functions (and therefore not on the basis of their specific strengths).

Only the roof joist[15] sometimes consisted of a material that did not coincide with those used for the other elements. This fact is probably due to the difficulty of finding beams of such a large size. A significant example can be found in the roof of S. Pietro in Vincoli, in which these elements —unlike the rest of the structure (made of chestnut wood)— were made of oak, from trees coming from several different places [16] and felled over a long period of time (20–30 years earlier than the trees used for the other roof beams). The chestnut beams, on the other hand, all came from the same place and were felled within a short distance of time from one another. It therefore seems that in this case it was not particularly difficult to procure them. In S. Maria Maggiore and in S. Clemente, on the other hand, also in order to obtain the quantity of material needed to make the shorter parts within a short period of time, it had been necessary to resort to supplies from several different places.[17]

This observation provide a plurality of cues for an investigation into the history of timber production and trade in the area around Rome, with reference to the organisation of large building sites. This topic could be particularly significant for the construction

of sub-regional dendrochronogical curves. Yet another question that will have to be investigated in depth in research studies concerns the greater or lesser availability of timber in different ages and the consequent adaptations brought about in construction techniques.[18]

General features of roofs: slope

In Rome, the roofs of large buildings are characterised by limited sloping of the pitches (about 24°), which was considered sufficient, already much earlier, to ensure good protection against the weather, considering the rarity of snow and the local rainfall trends. Contrary to what happened in Northern Europe, the angle of inclination of roofs has remained almost unchanged in Rome throughout the centuries. This statement is confirmed both by material evidence (traces of structures dating back to earlier times still visible in attics),[19] and by literary sources. The problem of what slope roofs should be given was actually already present in Renaissance treatises. Palladio, for example, wrote that»si partirà la larghezza del luogo da coprirsi in 9 parti, e di due si farà la larghezza del colmo» (Palladio 1570, Book I, chapter XXIX, 91), while Scamozzi, after recalling the teachings of Vitruvius, noted the ratios commonly adopted in his times: the height was equivalent to one quarter or to one fifth of the breadth (Scamozzi 1615, Book VIII, chapter XXIII). However, it was not until late in the 17th century that the problem began to be treated systematically, and general dissatisfaction due to the increasingly poor quality of roofs started to be recorded. At the same time, a growing tendency to set «quality standards» could be observed, and was to become even more marked in subsequent centuries. By way of example, Carlo Fontana's text *Templum vaticanum et ipsius origo* (1694) should be recalled here. Its central theme was clearly the building of S. Pietro in Vaticano, however it also contains some chapters on roofs. After describing the roof of the old basilica, Fontana considered the problem in general terms. In chapter XII, «*Causa perché sia necessaria l'ordinazione delli Tetti dalli Professori*», the author showered abuse on the «meccanici» who, not having sufficient knowledge of the rules, built roofs with the wrong slopes thus causing serious damage to constructions «Riconosciamo quasi un destino fatale, che la parte essenzialissima del custodimento de gli Edifizij, cioè li Tetti, abbi la sua esecuzione, & ultima ordinazione data in preda alli Mecanici; li quali ignoranti di quanto richiede il modo di divertire l'acqua tanto inimica; ordinano, & operano alla cieca, solo da una mera pratica; onde ne segue il lavoro imperfetto, per non avere le dovute pendenze. . . . Esortiamo Noi dunque gli intendenti Artefici, che fra le altre parti dell'Edificatoria, abbino particolarmente à cuore l'essenzialissima delli stillicidij, per evitare, e distruggere li modi improprij usitati dalli Mecanici» (Fontana 1694, 101). In the next chapter, therefore, he takes care to indicate the correct manner in which to approach the problem, suggesting two different slopes depending on how large the surface area is and well as on whether the roof is exposed to strong winds or collects rainwater also from other roofs. The rules suggested by him, on which it is not possible to dwell here, are summarised in Figure 2 and call for slopes varying between 19° and 23°. Roughly 150 years later, Valadier suggested similar solutions (23° for large roofs and 22° for smaller ones), however he warned against the danger of builders who tended, since it was more convenient for them, to make the pitch less steep.[20]

Geometrical constructions similar to that described by Fontana are used in Valadier's manual to define the correct proportions between the various elements making up *palladiana*-trusses (Valadier 1831, 43 and Plate LXVI). These scientific methods for determining the length of the beams were, however, not very widespread. Generally speaking, only rough indications are found which suggest a ratio between the rafters and the under-rafters of two third. These proportions can be found also in the historic structures preserved until the present day and appear to have remained constant over the centuries.

Masonry supports

Yet another feature of the roof structures found in Rome is the peculiar configuration of the way they fit in with the masonrywork. As a rule, the roof-trusses do not rest, as can be observed in other regions, on wooden wall plates but on brackets inserted directly into the masonrywork, and the main function of which is to contribute towards reducing the sag of the roof joist. The need for this support is a consequence,

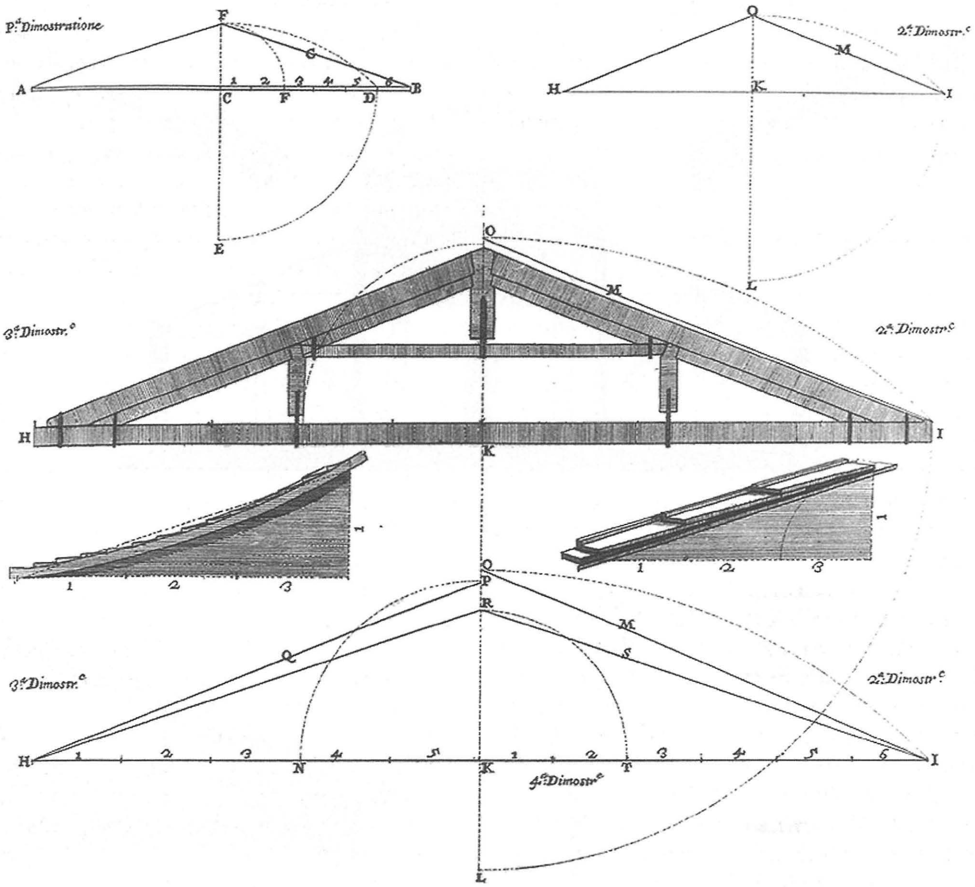

Figure 2
Fontana 1694, 105. Rules to define correct slopes by big size roofs

however, of other features of the structure as a whole. Indeed, in the case of *palladiana* trusses, in addition to rafters there are also under-rafters, so that the connection between the horizontal element and the slanting element is doubled, and is unable to rest on the masonrywork for its whole length. In order to avoid transmission of the loads from taking place at a «weak» point, it therefore became necessary to strengthen the support by means of corbels. Some indications in this respect are found in Valadier's treatise, in which the use of wood is preferred to stone for manufacturing these brackets: « . . . ve ne sono in qualche tetto che sotto le teste delle corde in luogo d'avere i modelloni di legno . . . sono modiglioni di pietra, che quantunque sembri un partito migliore pure in pratica non lo è perché se questo modiglione forza alquanto nella cima si spezza ed ecco a monte l'oggetto . . . » (Valadier 1831, 42). On the contrary Leon Battista Alberti upholds the thesis, that stone corbels are the best solution: « . . . quare placent apud veteres, qui assuevere parietibus lapideos mutulos firmissimos bene commendare, quibus quae dixi trabium capita imponantur». (Alberti [1485] 1966, book III, chapter XII, 229).

The fit between the wooden structure and the masonrywork is a particularly problematical area from the point of view of conservation, since in addition to the high risk of infiltration of moisture

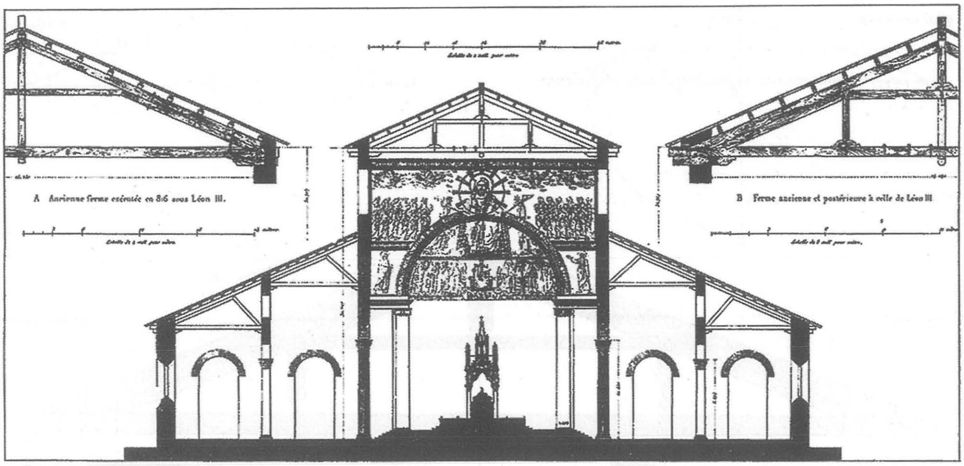

Figure 3
S. Paolo f. l. m.: cross-section and roof-trusses of the nave. Letarouilly1874, Plate 335 (Detail)

there is also the corrosive action of the mortar. Historic manuals and building contracts often contain the recommendation that the ends of the beams should be coated with pitch and that it had to be ensured that they only come into contact with bricks. As an alternative, it was possible to resort to a covering made of sheets of lead or similar expedients. It is also suggested that special care should be paid to setting up the supports which, while on the one hand they had to be made in such a way as to avoid rainwater entering, on the other they also had to ensure sufficient ventilation.[21]

It is probably for this purpose that the roof joists and the corbels of roman roof-trusses were not embedded in the masonrywork, but protruded instead from the other side of the walls on which they were resting. Some of the various possible solutions for this construction detail are described in the plates by Letarouilly, who surveyed in detail many roman roof structures (Letarouilly 1874). It is particularly interesting to compare the positions of the beams in the two construction typologies present on the central nave of S. Paolo f. l. m. before the fire in 1823, Figure 3. While in the case of the roof-trusses judged to be oldest by Letarouilly (made in 816, under Pope Leo III), the corbels and roof joists jut out from the wall, outside, by only 10–15 cm, in that of the roof-trusses built later these two elements are projected it by about

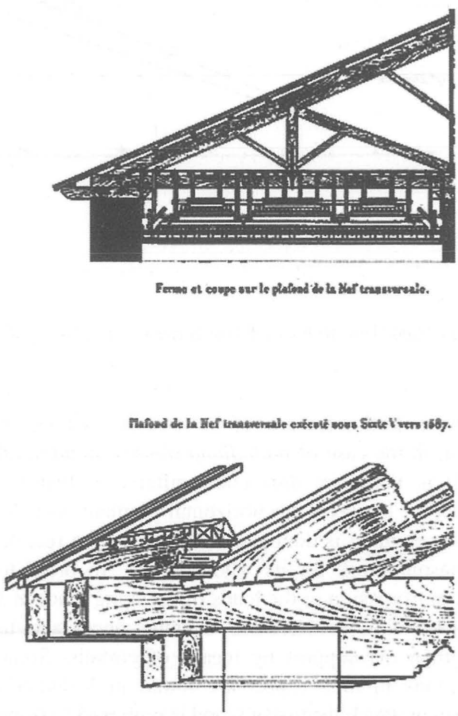

Figure 4
S. Paolo f. l. m., transept: details of the roof-trusses. Letarouilly1874, Plate 336 (Details)

1 m and 80 cm respectively. It appears that yet another different solution was present in the transept: the truss-rod did not protrude outside and ended, instead, flush with the wall, while the bracket protruded by about 1 m, Figure 4.

There is evidence of this variety of solutions also in existing ancient structures, and that differ greatly from one another as far as concerns these construction details. The truss-rods of the roof of S. Cecilia are visible from the outside but end flush with the wall, while those of S. Balbina for example extend outwards for a considerable length and those of S. Maria in Trastevere and S. Crisogono are completely embedded in the masonrywork.[22] Since in Valadier's plates two different solutions can be noted (one with the truss-rod embedded in the masonrywork and the other with the truss-rod and the bracket both protruding slightly), this would tend to point to simultaneous use, at least in the 19th century, of several different methods.[23] At this stage of our research, it is still difficult to say to what extent these different solutions were synchronic or diachronic, and only further research and finer dating of the wooden structures will enable this question to be answered.

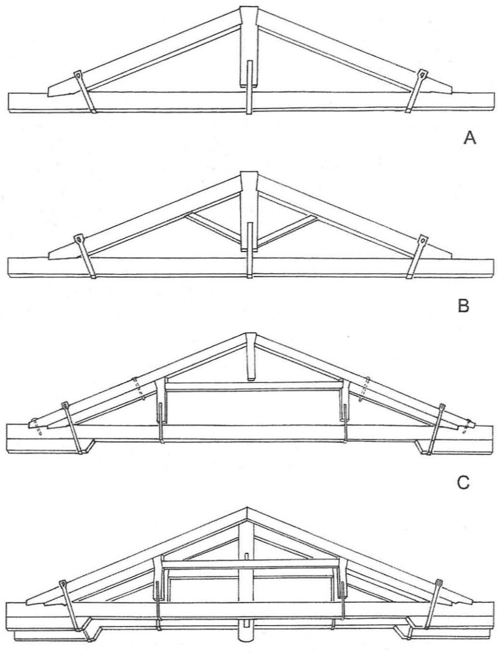

Figure 5
Most used structural typologies: A. Truss with a king post only, B. Truss with king post plus braces, C. simple *palladiana,* D. double *palladiana*

The relationship between the span to be covered, the structural typology adopted and the sizing of the parts

A fairly limited number of structural solutions was adopted for covering rooms with large spans. The less complex constructions were those with a single truss-rod (with a king post only or with a king post plus braces); then there are the simple and double *palladiane*, with their many variants, Figure 5.[24]

It has been found that several structural solutions were adopted indifferently over the centuries for dealing with the same construction problem.[25] The over twenty churches considered as samples had spans varying between 6.5 m and 24 m, and it was easy to observe that the choice of the construction typology to be adopted for their roofing did not depend on the width of the room, see table in Figure 6.

A single truss with a king post and braces may be found, for example, for covering spans varying from 6.5 to 13.40 metres, moreover without the elements being positioned closer together as the span to be covered became wider.[26] The double palladiana, which is the most complex of all the roof typologies found, was also used in a wide variety of cases, ranging from the transept of S. Maria in Trastevere, which has a span of only 8 metres, up to the main nave of S. Maria maggiore, which is 17.70 m wide. Again in this case, the distance between the single roof-trusses was not varied to any great extent as the span increased.[27] In spite of the apparently random way in which the various different construction typologies were chosen, it is clear that the structures do have some dimensional limits. The single *palladiana* and the roof-truss with king post and braces were not used for spans any greater than 14 metres, while the limit for the single roof-truss with a king post only was 11 m.[28] For spans greater than 14–15 metres, insofar as it has been possible to observe, only double *palladiane* were used. In spite of this, as has already been stated, they were also used to

Church	Span	Distance	Structural tipology
S. Pietro in Vaticano	24.25 m	—	Double *palladiana*
S. Paolo f.l.m. nave	24.30 m	4.00 m	Double *palladiana with* queenposts and kingpost
S. Maria Maggiore, nave	17.70 m	3.50 m	Double *palladiana* with queenposts and kingpost
S. Pietro in vincoli, nave	15.60 m	3.40 m	Double *palladiana,* just with kingpost
S. Balbina	14.67 m	3.25 m	Double *palladiana,* just with kingpost
S. Sabina	14.30 m	2.40 m	Roof-truss with king post plus braces
S. Cecilia in Trastevere	14.00 m	2.60 m	Simple *palladiana* with queenposts
S. Prassede	14.00 m	—	Double *palladiana*
S. Marcello al corso	13.40 m	6.50 m	Roof-truss with king post plus braces
S. Maria in Aracoeli	13.00 m	—	Double *palladiana*
S. Clemente	11.00 m	3.00 m	Roof-truss with king post plus braces
S. Maria in Trastevere, nave	11.10 m	2.70 m	Double *palladiana* 2 monaci
S. Lorenzo f.l.m., nave	10.67 m	4.00 m	Simple *palladiana* without king or queen posts
S. Spirito in Sassia	12.80 m	2.26 m	Simple *palladiana with* queenposts and kingpost
S. Maria in domenica	10.80 m	2.65 m	Simple *palladiana* with queenposts
S. Marco	10.40 m	—	Simple roof-truss without posts
S. Crisogono	10.00 m	3.00 m	Simple *palladiana* with queenposts and kingpost (connected with the roof joists)
S. Croce in Gerusalemme	9.90 m	4.50 m	Double *palladiana*
S. Saba	9.90 m	2.30 m	Double *palladiana* just with kingpost
S. Maria in Cosmedin	9.30 m 9.30 m	4.25 m 4.70 m	Roof-truss with king post plus braces Double *palladiana*
S. Maria in Trastevere, trans.	8.00 m	3.00 m	Double *palladiana*, just with kingpost
S. Pietro in vincoli, transept	8.00 m 8.00 m	3.50 m 3.50 m	Simple *palladiana* with queenposts and kingpost (not connected with the roof joists), Simple *palladiana* with king post (not connected with the roof joists)
S. Giovanni a porta latina	7.51 m	—	Simple roof-truss with kingpost
S. Maria maggiore, transept	6.50 m	2.60 m	Roof-truss with king post plus braces

Figure 6
Relationship between the span to be covered and the structural typology adopted. In the second column the distance between the single roof-trusses

cover relatively small spaces, for which simpler construction solutions would have been equally adequate.[29] Double *palladiane* were made in many variants that differed from one another in terms of the number of king posts. The known examples tend, however, to show that the number of intermediate

supports was not necessarily increased as the span increased. The example of S. Paolo f. l. m. is significant in this context. According to the survey published by Letarouilly, there were two different types of double *palladiane* covering the main nave, which was 24.30 m wide. Some of them had a single central connecting king post, to which in the others three more were added for each element, Figure 3. According to Letarouilly, these were two separate works dating back to different periods, of which the oldest was probably built under Pope Leo III (816 ca.) (Letarouilly 1874, Vol. III, Table 335–336, Letarouilly 1868, 696). Their simultaneous presence bears witness to the fact that the use of a larger number of king posts was not due to a construction requirement. Rather, it probably depended on the customs of the workmen and/or of the designer. An interesting indication in this respect is found in the treatise by Krafft, which established a relationship between the number of king posts required in order to ensure stability and the quality of the material used. In the case of softwood such as fir, which is less strong, it was necessary to increase the number of intermediate supports: «Ces dimensions varient selon l'espèce et même les qualités des bois que l'on vent employer. Ou peu alléger les ajustements qui doivent étre exécutés en bois blanc: mais il n'en est pas de même pour les bois durs, et fon ne doit jamais perdre de vue qu'il s'en fant de beaucoup que l'on puisse compter sur la solidité des tenons ni mème des embrèvemens des bois blancs, et que c'est par cette raison qu'on multiplie de preférence les moises dans les charpentes d'une grande portée qui s'exécutent en bois de sapin». (Krafft 1822, Chapter 5, Preface).

As seems to be confirmed also by Krafft's text, these variations of the double *palladiana* might have been present together over the centuries, without being typical of any particular period.

Another significant parameter is that concerning the cross-sections of the single elements of which the roof-trusses were made up. In this respect, it has been observed that they were not affected to any great extent by the increase in the distance between the supports. It should in any case be considered that some structures were designed not only for the purposes of the roof but also for supporting the underlying ceilings.

Conclusion

The research carried out in the framework of the Project «*Indagini dendrocronologiche in chiese paleocristiane di Roma*» highlights the fact a preference was found in the buildings analysed for chestnut wood, while fir and oak were also frequently used. No direct indication was however found between the function of a specific element within the structure and the material used to make it.

Unlike central and northern Europe, where construction typologies, the way in which the various parts are connected and the building techniques have changed significantly in time, so that it is possible to develop a reliable chronotypology, in the Rome area it was observed that the same forms remained constant for centuries, subject only to very minor changes. The metal components used for connection purposes, on the other hand, featured significant diachronic variations. From the structural point of view, it is interesting to note how the choice of the construction typology was not, in most cases, directly related to optimisation criteria. Relatively complex forms were used even to cover small spans.

As far as concerns dendrochronology, the first results relating to the processing of several master chronologies referred to central Italy and in particular to the Lazio region were obtained during the course of the study. It will, however, be possible to refine the dendrochronological curves and to extent them only after extending the research to other buildings and collecting additional samples for increasing the statistical base. In this respect, investigations concerning the places of origin of the wood and drying techniques and times must also be considered essential for providing significant parameters for determining the date of actual use of the components, starting out from the determination of the years in which trees were felled. In this respect, however, it has been found that there are very few economic and forestry history studies capable of providing a reliable knowledge base for going into this issue in greater depth in central Italy.

Another chapter that is still open but that holds some promise of interesting developments concerns the history of the way in which building sites were managed and construction-related thought concerning the single elements. The sources analysed so far, which consist of material and written evidence, have

shown that they could form a significant starting point for further studies on whole buildings, which is an approach rarely considered when studying construction techniques. It should be noted, indeed, that investigation of roofs and of the rooms immediately underneath them often provides a valuable opportunity for discovering and studying traces of construction stages that influenced the development of the whole building. During the course of our research, for example, data were acquired that had been ignored up to now by the albeit abundant historic and architectural literature and which provided cues for clarifying the history of several basilicas, including those of S. Cecilia in Trastevere, S. Croce in Gerusalemme and S. Clemente.

NOTES

1. The project is being conducted by the T.U. Berlin (Prof. J. Cramer), the Westfälische Wilhelms-Universität of Münster (Prof. H. Brandenburg) and the Università della Tuscia of Viterbo (Prof. E. Corona and Prof. M. Romagnoli), and is being financed by the Gerda Henkel Stiftung.
2. The work was carried out in the framework of the Research Doctorate in Kunstwissenschaft, Bauforschung, Denkmalpflege of the TU Berlin and of the Otto Friedrich Universität Bamberg, with a thesis, currently being completed, called «Contributi per una storia delle strutture di copertura delle chiese di origine paleocristiana a Roma».
3. An illustrious example of this approach consists of the studies by P. Marconi, A. Pugliano and F. Ragazzo contained, among other things, in the various *Manuali del recupero*. In particular, reference has been made here to the two editions published by the Rome City Council (Giovannetti et al. 1988; Giovanetti 1997).
4. In this context, G. Tampone should be recalled, with his numerous and significant publications on this subject, but also other authors, such as, for example, C. Bertolini, Barbisan and Laner (Barbisan and Laner 2000).
5. See De Berénger 1859–1865.
6. Classical works mention many species of trees, however here only those considered most usual in carpentry are recalled.
7. These percentages cannot, however, mirror exactly the ratios existing in the roofs. This is because the samples were not taken everywhere but starting out from groups of elements selected on the basis of various different features: the material, the traces showing that they had been worked, the fact that they belonged to given stages of construction. 5 to 15 carrots were extracted for each homogeneous group, depending on the boundary conditions and on the number of available elements. For further considerations concerning the species used in the Middle Ages and in the Modern Age, see subsequently.
8. Chestnuts were already mentioned by Homer and then by Virgil.
9. Cattaneo (Cattaneo 1554, 2. VIII), also, reports something similar, although he maintained that this plant originally came from Sardinia: «Venne questo arboro di Sardegna. & però i Greci chiamavano il suo frutto balani Sardiani, cioè ghiande di Sardegna: perché Balano in Sardegna significa ghianda. Tiberio Cesare pose di poi questo nome balano alle castagne, che per innestare erano divenute migliori . . . ».
10. According to Nisard (Nisard 1851, 521), Palladius Rutilius Taurus Aemilianus's work is said to have been written between 371 and 395 AD. The similarities and differences between Palladius's work and those of his literary models have been thoroughly analysed by Plommer (Plommer 1973).
11. The architraves from S. Stefano Rotondo, dated back to 451 BC, unfortunately only had 40 rings, and therefore their dating cannot be considered certain. The samples were, however, characterised by a growth trend similar to those recorded for some oak beams from the roof, also dated as mid-5th century.
12. On the subject of the use and development of the chestnut in the Middle Ages, compare Cherubini 1981; Montanari 1979, 34–43. In particular, with reference to the Lazio region: Toubert 1973, 1, 161 set seq. and 191–192; Cortonesi 1988, 307–319; Ferrantini 1947, 16–30.
13. It is in any case necessary to consider these occurrences in a differentiated manner, since the wood coming from plants selected for the production of fruit is not very suitable for building purposes.
14. «Il legname ne» Solari, ò siano Tasselli, Coperti, & anco per li ponti, & armature, non devesi adoperare di varie forti, quando ciò si possa fare di meno, mà adoperare legno dolce con simile, ma non col dolce mischiarvi Querza, ò Rovere, & altri simili legnami forti, quali non convengono assieme, e difficilmente si possono congiungere, & inchiodare assieme . . . «(Spinelli 1708, 102).
15. There is clearly a long-standing tradition in this respect. In the roof of the church of S. Caterina on the Sinai (6th century) as well, the beams are all made of the same material (fir) except for the truss-rods (cypress). Targeted use of elmwood has been recorded in Tuscany, where it was employed (together with oak) for building the king posts (information kindly supplied by Prof. G. Tampone).

16. This statement is based on the analysis of the parameters referred to the growth trend and of the degree of similarity between these values as found for the samples analysed dating back to the same period (t = 0.54 – 2.52, mean value for the same species in the region considered: 6; GL (percentage of agreement) for S. Pietro in Vincoli = 59.7 – 73.8, mean value for the same species in the region considered =70). On the subject of the scarcity of timber in the Lazio region in the Middle Ages, see: Cortonesi 1988, 306 et seq.; Toubert 1873.
17. In this as in many other cases, a discrepancy can be noted between actual construction practices and the rules suggested in treatises. See also L. B. Alterti's recommendation referred to above, calling for the use of trunks coming from the same forest.
18. This is because, in given cases, a tendency to minimise the quantity of wood used or to adapt the structures so as to promote the use of beams having a smaller cross-section or of shorter lengths has been observed. The purpose of this was to overcome the problem connected with finding large beams. A very interesting paper concerning this problem in France is the document by Bechmann, 1984, 191–225. A first investigation referred to the situation in Rome was carried out in the framework of the project illustrated here.
19. It was possible to observe a discrepancy between the slopes used currently and those used in the past in the transept of S. Maria in Trastevere, up to the 16th century, equal to 30° (currently 23°), and in S. Maria Maggiore, where the 12th century roof had a slope slightly greater than 20° (currently 25°).
20. «Questi metodi equivalgono il dire, di dare al tetto una pendenza di quattro palmi a canna, ovvero nel secondo esempio palmi quattro e mezzo; qui convien che si avverta, che generalmente i muratori non amano, e se non ci si bada, non danno alli tetti che poco sopra li tre palmi, e mezzo a canna, poiché le riescono meno incomodi da praticarvi, poco curando che quando sia terminato il tetto passino le acque pluviali a danneggiare l'intero fabbricato» (Valadier 1831, 33).
21. Alberti [1485] 1966, book III, chapter XII, 231; Serlio 1584, book IV, 135; Scamozzi 1615, book VII, chapter XXVI, 255. See also Pugliano 1997, 50
22. In this respect, it should be noted that most buildings had undergone restoration work on several different occasions and had been tampered with during the course of the centuries, so that the current situation does not necessarily correspond to the choice made originally at the time of construction. However, in most cases, the restoration operations were carried out re-using all or part of the existing materials, so that the length of the roof joists and the relationship between them and the corbels and the masonrywork may have remained unchanged.
23. Valadier felt that it was wrong and dangerous for the conservation of the roof joists to position it so that it protruded outside the building. In his opinion this solution was also aesthetically unsatisfactory (Valadier 1831, 35–36).
24. This type of structure is not always defined as a *«palladiana»*, and indeed it is not an invention of the famous architect. Nor do the structures suggested by him correspond exactly to those currently indicated with that word. For simplicity's sake, this name (which is, moreover, fairly common in contemporary literature) will be used in any case.
25. Some buildings were studied in situ, while for the other the information was taken from research studies either already published or about to be. In particular I wish to thank architect F. La Gualana, who placed his degree thesis at disposal (La Gualana 1987).
26. S. Maria Maggiore, transept: span of 6.5 m, distance between roof-trusses 2.6 m; S. Maria in Cosmedin: span of 9.3 m, distance between roof-trusses 4.25 m.
27. 3,0 m in S. Maria in Trastevere and 3.4 m in S. Pietro in Vincoli.
28. Accordino to Scamozzi the roof-truss with a king post and braces is a suitable solution for spans between 30 and 40 feets, the single palladiana with three king posts for spans between 50 and 70 feets (Scamozzi 1615, book VIII, chapter XXII, 343–344). According to Valadier, the roof-truss with a king post and braces is a suitable solution for spans not exceeding 40 palms (8.96 m). Based on an analysis of archive documents, A. Pugliano maintains that roof-trusses with a king post and braces were usual up to 70 Roman «palms» (15.6 m), while those consisting solely of a king post, rafters and a truss-rod did not exceed 25 palms (5.6 m) (Pugliano 1997, 50). These limits are contradicted by structures that actually exist, such as the roof of the church of S. Clemente (a span of 11 m covered by a king post and braces structure) and the transept of S. Pietro in Vincoli (a span of 11 m covered by a single roof-truss with only one central king post, alternated with single *palladiane*).
29. See, for example, the case of the transept of S. Maria in Trastevere, which is «only» 8 m wide and is covered by a double *palladiana*.

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Research on built heritage contributes to sustainable construction for the future

Koenraad Van Balen

Research on heritage at the European level is endangered, as it seems not clear to policy makers how this research contributes to a better living for European citizens. This situation has been brought to the attention of researchers and politicians at various occasions. Questioning this situation, it appears essential that the relation between understanding the properties (a.o. durability) of architectural heritage or ancient construction techniques at one side and sustainable construction at the other side should be clarified. A first attempt to identify the possible contribution of heritage research to development of sustainable construction is proposed.

This paper intends to open the discussion to complete this picture. It starts from an understanding of the perception on which this new interest in sustainability is based, it tries to identify a paradigm which was governing an important part of the research on modern construction techniques and that led to overlooking durability aspects of some ancient construction techniques.

The architectural heritage and the knowledge on ancient construction techniques (a form of intangible heritage) are an invaluable «archive» of sustainable building solutions that heritage conservators and scholars in construction history should explore, contributing to a more durable construction for the future.

Need for a debate

Research on physical aspects of the built heritage at the European level is endangered, as it seems not clear to policy makers how this research contributes to a better living for European citizens. This situation has been brought to the attention of researchers and politicians at various occasions as for example at the Vision Workshop, European City Vision – Defining Research Needs in Brussels on 8&9 February 2001 and at the European Parliament (Cassar e.a.2001).

Meanwhile the outline of the newest research framework of the European Commission has mainly reduced the means for research on heritage to the field of information technology, which is a considerable alienation from the European research carried out on the sustainability of the physical heritage.

Therefore it appears essential that the relation between understanding the properties (a.o. durability) of architectural heritage or ancient construction techniques at one side and sustainable construction at the other side should be clarified. A first attempt to identify the possible contribution of heritage research to development of sustainable construction has been proposed but requires more investigation and needs to be debated (Van Balen 2001).

Interest in sustainable development is pushing research today as it expresses one of the main challenges for surviving of mankind on earth. In the

framework of a congress on construction history the focus is on the benefit research on sustainable construction can take from a thorough analysis of ancient building practices. Such a link would also give even more credibility to research on construction history.

Understanding driving forces in past and new research on construction technology and building materials

Participating to the symposium «The Cultural Heritage of Asia and the 21st Century» at the Institute of Asian Cultures, Sophia University in Tokyo (September 21–22, 2000) I realized that one of the speakers was using the words «Universal» and «Global» the one for the other. Although their meaning is not similar in the context where it was mentioned, both of them could have been used. It shows that ideas are not clear yet and require more reflection.

Similarly many international guiding documents dealing with the way heritage values should be defined and embedded in the management of heritage sites are developing new concepts integrating the layered concept of values. Australian and Canadian scholars and heritage authorities are contributing significantly to that discussion.

The following reflections aim at contributing to an explanation on the essence of our actual concern for sustainable development. It might also help us to direct scientific research and technological developments for a sustainable development of the habitat of tomorrow and position the research field of the participants of the colloquium in that debate.

Definitions revealing concepts

Studying the issue of authenticity related to heritage, it could be noticed that there is a fundamental difference between the viewpoint of the person attributing «universal» versus «global» to values or authenticity.

Let us consider some definitions:

> Universal: n. 1. the whole; the general system of the universe; the universe. 2. (logic) (a) A general abstract conception, so called from being universally applicable to, or predicable of, each individual or species contained under it. (b) A universal proposition. See Universal, a.,
>
> Universal: a., 1. Of or pertaining to the universe; extending to, including, or affecting, the whole number, quantity, or space; unlimited; general; all-reaching; all-pervading; . . . 2. Constituting or considering as a whole; total; entire; whole; . . . 3. (Mech.) Adapted or adaptable to all or to various use, shapes, sizes, etc.; . . . 4. (Logic) Forming the whole of a genus; relatively unlimited in extension; affirmed or denied of the whole of a subject; . . . (Webster's Revised Unabridged Dictionary, 1996, 1998, MICRA, Inc.)
>
> Global: adj.: 1. Having the shape of a globe; spherical. 2. Of, relating to, or involving the entire earth; world-wide, . . . 3. Comprehensive; total (The American Heritage Dictionary of the English Language, Third edition, 1996, Houghton Mifflin Company.)

Those words express the difference in concept between the age of modernity (the years of the birth of the Venice Charter) and the nowadays post-modern era.

During modernity there was a belief in (unlimited) progress and prosperity; human kind was seen as Universal. Man was facing the universe as a kind, looking from the earth to the universe as a pilot who sees his spaceship traveling through the solar systems. Satellites with one representation of mankind have been sent to planets and the solar system. Modernity is the sense that the present is discontinuous with the past.

In the field of architectural conservation, the charter of Venice expressed this concept in a single approach to conservation, being valid for the kind: the Universal mankind. The Charter of Venice nevertheless did consider a concept of continuity in the essence of its objective while integrating a concept of discontinuity in the architectural development of interventions and the use of materials. It was ambiguously modern and traditional.

Together with this universal perception we notice that science was based on a paradigm using a rather deterministic approach (as could be illustrated in e.g. the problem of modeling safety assessment of historic buildings) and the belief that the reality could be

modeled and understood through a limited set of parameters. The number of parameters was expected to be as limited as possible, replying to the request of producers to be able to standardize and carry out simple quality control. An example of the latter is the use of standards (for materials, quality assessment) and the extreme extensive conclusions made about the structural behavior of historic structures using simple models of understanding.

Similarly it seems that durability was not really an issue in the development of materials for construction based on the lacking of that criterion in the investigation. The consequence of the discontinuity with the past concealed the possibility to use the past for understanding the future. In this modern concept, and I refer to research on mortars it was assumed that the stronger and rigid mortar would probably be also the one that was to be preferred for new constructions and for repair of monuments. Nowadays we assume that we could learn from the past behavior of materials (e.g. lime mortar) to develop adapted repair material.

Today the perspective seems to change into a perspective from outside of the globe to our planet earth, as is the perception of an astronaut. This is the global perspective that has to be aware of the variety of species, cultures and types of human beings. Diversity becomes a key issue and as demonstrated by the ecological movements this diversity is a necessity for future existence of the planet.

Similarly we should consider the need for diversity of cultures, taking into account not only the geographical diversity but also the historical diversity (diversity over time) at the same places. This makes things complex, but today we accept the notion of complexity, the fact that not everything can be under control. Chaos-theory, developments in mathematics and computers have made us aware of this inherent complexity of the world, the complexity of our ideas and our limited possibility to «control» our perception of the world, limits on the control on the outcome of our actions as human being. Deterministic models have made place for probabilistic models.

To say it with the words of Richard Hooker: «You can see, then, what characterises modern abstraction in a wider sense: it is the loss of standards or universals. In the place of standards we have instead only the logic of internal relationships and internal design. In such a worldview, there is little effort to integrate one sphere of human understanding with another; the modern human existence is one of fragmentation. We approach the community of humanity and we approach our own lives as made up of independent fragments that each operate on their own logic. Of all the cultural anxieties of the twentieth century, this abstractiveness and fragmentation has consistently been acknowledged as the most serious crisis of modernity.»(Hooker 1996)

With other words methods and procedures that must be transparent and consistent are replacing standards.

The implications are that we have to define a new of approaching a number of problems and we have gradually started to do so. For the field of sustainable development this can be expressed through the following: there is not such a thing as a unique (universal) development strategy instead we should recognize diversity in the approach.

If diversity should be considered in geographical terms but also in time, «heritage» becomes an interesting issue as in the discussion on understanding the past examples of (less or more) sustainable development we can get valuable information about the future sustainable development we are looking for (see later in Contribution of the heritage).

Consequences

The complexity this assumption generates is frightening as we start to question if we have the knowledge to give the necessary answers to our concerns for a sustainable development of our cities and habitat. For a long period covering the «modernity» we have been used to think in limited terms and «universal» solutions. Research has been directed in this way in the past and thus over-simplifying the reality: deterministic approach, standardization. It is clear that research and technological developments of the past have to be rethought within this framework.

A few questions that have to be solved resulting from this new perspective are:

1. Are standards used for materials for example in the building industry, adapted to this new concern for durable and sustainable constructions? (European) Standards for construction materials and safety issues are merely based on new buildings and new materials while the building

renovation and restoration is becoming an increasing part of the construction activities. Those standards are also based on oversimplified models of reality. Problems arise very often when an increasing part of the building stock is reused or renovated. It suffers difficulty to be in accordance with those standards while their renovation and reuse can be in accordance with requirements related to sustainable constructions, safety and the quality of life requested by the citizens.

2. Do we have models to predict behavior of materials, mobility, social behavior and safety for the far future or do we have instead to think in terms of small time steps predictions and base our understanding and steering on good systems of monitoring and continuous feedback? This might be very much the same as what F. Ascher names «the reflexivity» referring to A. Giddens.
3. Do we have adapted technologies that help decision takers and actors in the field to monitor changes and deduce proper actions? This is not only at the level of planning «The difficulty of planning the physical environment is that the feedback loops are too long.» —Stewart Brand—, but also at the technological level.
4. Nowadays interdisciplinary research seems to become more and more evident, this results from the understanding of the interaction of research fields, the different possible actors and inherent acceptance of complexity. How can we improve this collaboration and research to be really interdisciplinary, to make sure that interaction between actors occur but also that interaction between fields covered by different sciences and technologies is understood.

EXPLOITING RESEARCH RESULTS ON CONSTRUCTION HISTORY IN A DIFFERENT WAY

New problems arise today but the same time mankind has faced many problems since long time. Studying the remains of how past generations have been dealing with those issues can than become very interesting and its preservation serve the purpose to keep a kind of a library or archive of solutions (in physical and conceptual terms). This throws a new insight on the reason to take care of our heritage as a stock of solutions for future generations. This is the case as well for movable as for immovable heritage, for monuments, for pieces of arts in our museums, for archives. Heritage is thus an important asset for sustainable development.

At the same time scientific research is needed to understand how this heritage has contributed to solving problems dealing, as in our case, the sustainable habitat of tomorrow.

Heritage contributes to the understanding of durability, as its reaction on air pollution, climate changes, etc. is more realistic than any laboratory simulation or mathematical model. Organization developing European directives on air quality start to use existing research data and they request additional research on the effect of air pollution on the heritage to be able to include long-term accumulated effect on human being and materials in their guidelines for the future.

Research on the history of ancient building technology can reveal information that can't be understood from a physical analysis of the constructions alone. This research on physical expression of the building should thus be completed with information on the global historical, technological and social context to complete the understanding allowing its transfer in new construction methods and in repairs techniques.

A good illustration can be given through the research on old lime mortars. Recent research summarized and referred to in the contribution in this conference «Understanding the lime cycle and its influence on historical construction practice» show how research on construction history can contribute to knowledge on the «savoir-faire». This should complete the scientific information acquired from material and physical analysis and from the study of the degradation history. A similar all encompassing methodology is being developed in RILEM's Technical Committee -167COM «Characterisation of Old mortars With Respect to Their Repair» (Bartos 2000) and has been addressed in an EC project Maintenance of Pointing in Historic Buildings: Decay and Replacement (Van Hees 2001).

INVITATION AND CONCLUSIONS

The paper aimed at opening a debate on the role and contribution of the research carried out in the field of

construction history. It is argued that this discipline could have an increasing contribution to the development of sustainable constructions for the future, taking into account a global sustainable perspective. The development of arguments is still in progress and the author welcomes all reflections and contribution on the topic with the objective to make them public and help steer research policies to consider the valuable input this field of research can give.

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Understanding the lime cycle and its influence on historical construction practice

Koenraad Van Balen

Burning, slaking and carbonation are the major steps in the lime-cycle leading to the air-hardening of lime mortar. Lime mortar has been used since antiquity. Its preparation and its use have been understood by generations although during time schemes of understanding have changed.

Looking today at historical perceptions of the lime cycle helps to identify the proper understanding of certain material properties and the use of lime mortar in the past.

First the lime cycle is explained based on actual chemistry and mineralogy. Looking at some well known writings of Vitruvius, Renaissance authors, C. Perrault, 18th century authors, the evolution of the understanding of the role of heat, water, air in the preparation and the use of lime becomes clear.

Impurities in the limestone selected for burning can be responsible for hydraulic reactions in lime considered too often as being only air-hardening. Interpreting sources as Vitruvius and later ones we could deduce that such stones have been selected to prepare lime. This demonstrates that also hydraulic hardening is to be considered beside carbonation if some constrains are respected. This understanding throws a new insight on what is hydraulic lime and could contribute to a better use and standardisation of building lime, even today.

Some ways to prepare lime (e.g. dry slaking) have been investigated in laboratory conditions. Lime mortars with a similar appearance as historic mortar samples could be produced. Dry slaking solves a number of problems met today in using building lime and is compatible with the use of hydraulic lime if impurities were present in the burned limestone. It seems obvious that different types of lime could have been used for different applications with lime.

The objective of this paper is to explain thoroughly the use of lime as a building material and to relate different types of lime to certain types of application in construction history as we can know from actual scientific knowledge confronted with some historical sources.

Introduction

This paper aims to clarify different ways to prepare lime and to explain in which way this preparation influenced the use of lime over time. The understanding of the «lime cycle» and the hardening of lime and hydraulic lime over time is the subject of this contribution. Recent research has contributed to a better understanding and therefore this information will be used to update information that, although known to some, was not available to a wider scientific audience.[2] This paper will concentrate on the North-Western experiences and context although for its «origins» of understand we have to start in the Mediterranean Basin.

So far one of the most important and often referred to source of information on the use of lime in mortars in antiquity is Vitruvius. Most of us today refer to translations of this document. Progress in understanding the properties of materials have certainly also induced some new interpretations and translations of Vitruvius «Ten books of architecture» (Vitruvius [25 B.C.], 1914). In the case of the sources of hydraulic binders new interpretations have been proposed by F. Davidovits (1994) and also by others based on a better integration of natural with human sciences.

Our contribution begins in the Roman period acknowledging however that lime mortar was used earlier by the Greeks mainly for rendering. They used sand that sometimes was from volcanic origins as explained by Roland Martin (1965), amongst others. Mortars for rendering also contained plaster and marble powder. The use of earth of Santorini and crushed ceramics showed that Greek were able to increase hydraulicity of the mortar artificially. The product made in this manner is the predecessor of the artificial pozzolana (Furlan and Bissegger 1975).

Roman lime mortar.

Romans developed and utilized the technology of lime mortar and lime concrete. They even used different aggregates to control the density of the concrete with lime in a way to assure the stability of domes (Lamprecht 1986).

The extent of the Roman Empire is at the origin of the wide dissemination of this knowledge in Europe and around the Mediterranean Sea.

One of the oldest descriptions of «opus caementicum» can be found in the writings of Cato the Elder (234–149 B.C.) (Van Tyghem 1966). He described a construction «ex calce et caementis». Vitruvius gives the most accurate description of the composition and the use of lime mortar. In his book «Ten books on architecture», probably a good description of the building practice at that time (Adam 1984, ref. 113), different data are given on the technology of lime mortars at that time (Vitruvius [25 B.C.] 1914, 45).

> After slaking it (lime), mix your mortar, if using pit sand, in the proportions three parts of sand to one of lime; if using river or sea-sand, mix two parts of sand to one of lime . . . , in using river or sea sand, the addition of a third part composed of burnt brick, pounded up and sifted, will make your mortar of a better composition to use.» (Vitruvius [25 B.C.] 1914, II, V, 1)

Although we concentrate on the lime cycle (burning - slaking - carbonation) it should not be forgotten that the use of inert fillers (as sand) and reactive fillers (as pozzolanic materials) were understood to change the properties of lime mortar. Sea-sand seems is a lesser quality sand to use according to Vitruvius because there is the danger for efflorescence.

Although they had no proper —in our terms— explanation for it, the Romans new that adding earth from Puzzuoli (and other places like the hills of Mysia in the west of Turkey, in the surroundings of Mount Etna) give mortar hydraulic properties.

The Romans made the link between the volcanic origin of the earth and the property and they tried using their philosophy of nature to give an explanation.

Vitruvius suggested using this pozzolana to make the mortar resistant against water.

Although the Romans knew natural pozzolana, it seems that they were not able to choose the right limestone to make natural hydraulic lime. It has been shown that Romans in Great Britain made hydraulic lime with high calcium and artificial pozzolana as powdered tiles instead of using the clayish limestone in the direct environment with which it should have been possible to make natural hydraulic lime (Davey 1961, 104).

Pliny the Younger, Seneca and Sidonius Apolinaris also wrote about the effect of the use of natural pozzolana on lime mortar (Ferrari 1968).

Many legends exist about the secrets of the composition of good Roman mortars and about the use of additives as egg white, casein and oil. Probably those additives add to lime mortar, were reserved for particular applications. Oil has been used in the mortars for the sealing of ceramic water pipes (Malinowski 1979, Malinowski 1981, Malinowski 1982) and also Vitruvius described the use of oil for the sealing of the joints of watertight floors. (Vitruvius [25 B.C.] 1914, VII, 1.7.)

Raw materials and treatment.

Apart from the composition the choice of the raw material and the treatment were also of great importance to the quality of the Roman mortar (Frizot 1977).

When lime mortar was used for massive parts of masonry and floors the lime mortar was well rammed whereby its density increased. The execution of rendering in different layers with different composition and the polishing at the end influenced the water transport in the mortar and also the carbonation process (Malinowski 1979, Malinowski 1981, Malinowski 1982). All evidence seems to indicate that the good quality of the Roman mortars was due to a good control of the firing process of limestone, the homogeneity of the mortar (concrete) and the skilful application.

Burning of lime

J.P Adam (Adam 1984, 69–90) distinguishes three types of burning in the Mediterranean region in antiquity:

1. The first is the burning in a kiln in which the fire is made at the bottom and the kiln is filled with limestone lumps. The firing is discontinue as the burned stones have to be taken out at once from the whole kiln, this is an intermittent type of kiln
2. The second way is burning in a kiln filled with alternating layers of limestone and fuel. Burned limestone is taken out at the bottom while new layers of limestone and fuel are brought in at the top. The firing is continued, as the firing does not have to stop when the quicklime is taken out; this is a continuous type of kiln
3. The third method is the firing in open air. This method can only be used at lower temperature as for gypsum stone to prepare plaster.[3]

Cato the Elder prescribes the construction of a kiln, dug into in a mountain slope so as to avoid cooling by the wind. The homogeneity of the temperature in the kiln at about 900°C was very important for the quality of the lime (Adam 1984; Van Balen 1991).

In some regions with much rain, the top of the oven was closed to avoid fast cooling and some circumferential holes were used for the evacuation of the smoke and to fill the kiln. We don't know whether such kilns were used in the North-West of Europe at that time. We do know that more recent kilns in the region of Tournai had an opening at the top by which it could be filled. From the Roman period, the archaeological remains of one Roman kiln have been found in Tournai (Chantry 1979).

The slaking

Slaking often occurred at the unloading dockyard, as the transport of quicklime was less heavy. Smaller quantities were transported in amphora at sites where it was not possible to slack lime (Adam 1984, p.78, fig. 160) and to keep it for a certain time.

Slaking has to guarantee that all quicklime has turned to calcium hydroxide. Therefore the lime had to lie in pits for a certain time before being used it in mortar; Pliny prescribed 3 years (Adam 1984, ref.108). For the same reason a good mixing and knocking up of sand and lime is important. This was done with a lime chopper (the Roman *ascia*) that was able to crush lumps in the quick lime.

There is a strong prejudice that considers that this is the only way slaking occurred. More and more research is filling the gap that existed in our knowledge on the use of high calcium lime versus hydraulic lime. This allows us thus to consider a variety of ways of slaking and preparing lime and lime mortar.

Roman understanding of the lime cycle

The term «lime cycle» is generally used to describe the sequence of processes leading from limestone ($CaCO_3$) to Carbonated lime ($CaCO_3$) being again of the same chemical nature. Intermediate processes are the *burning* changing $CaCO_3$ to CaO (quicklime) followed by the *slaking* changing CaO into $Ca(OH)_2$ ((slaked)lime or portlandite) and followed by the *carbonation* or hardening changing into $Ca(OH)_2$ into $CaCO_3$.

In his second book, chapter V, §2 and §3, Vitruvius explains the lime cycle. He describes how lime mortar hardens and how lime can be used to make mortar:

> The reason why lime makes a solid structure on being combined with water and sand seems to be this: that rocks, like all other bodies, are composed of the four elements. Those which contain a large proportion of air are soft; of water, are tough from the moisture; of earth, hard; and of fire, more brittle.
>
> Therefore, if limestone, without being burned, is merely pounded up small and then mixed with sand and so put into the work, the mass does not solidify nor can it hold together. But if the stone is thrown into the kiln, it loses its former property of solidity by exposure to the great heat of the fire, and so with its strength burnt out and exhausted it is left with its pores open and empty. Hence, the moisture and air in the body of the stone being burned out and set free, and only a residuum of heat being left, lying in it, if the stone is then immersed in water, the moisture, before the water can feel the influence of the fire, makes its way into the open pores; then the stone begins to get hot, and finally, after it cools off, the heat is rejected from the body of the lime.
>
> Consequently, limestone when taken out of the kiln cannot be as heavy as when it was thrown in, but on being weighed, though its bulk remains the same, it is found to have lost about a third of its weight owing to boiling out of the water. Therefore, its pores being thus opened and its texture rendered loose, it readily mixes with sand, and hence the two materials cohere as they dry, unite with the rubble, and make a solid structure.

According to Vitruvius the burning is necessary to open the structure by which it can glue together to the other materials in the mortar.

Effect of pozzolana.

In his book II, chapter 6 Vitruvius wrote about the mixture of lime and volcanic sand to make a mortar resistant to water and even able to harden under water. He gave the following explanation:

> the soils on the slopes of the mountains in these neighbourhoods (where pozzolana are found) is hot and full of hot springs. This would not be so unless the mountains had beneath them huge fires of burning sulphur or alum or asphalt. So the fire and the heat of the flames, coming up from far within through the fissures, make the soil there light, and the tufa found there is spongy and free from moisture. Hence, when the three substances (lime, pozzolana, tufa), all formed on a similar principle by the force of fire, are mixed together, the water suddenly taken in makes them cohere, and the moisture which neither the waves nor the forces of the water can dissolve.

Ancient authors stressed using pure limestone to guarantee a good quality of lime.

The quality was controlled by weighing the loss of substance with burning. This allowed some scientists to conclude that this certainly must have been the prime reason of the late discovery of natural hydraulic lime (Alou 1989, p.5). Romans have been said to make their hydraulic mortar by adding natural (pozzolanic earth) or artificial (crushed tiles) pozzolanic additives rather than to use nearby sources of limestone able to produce hydraulic lime (Davey 1961).

We should however have questions about these conclusions for a number of reasons

1. According to Vitruvius a good limestone for producing lime should lose about one third of its weight (Vitruvius [25 BC] 1914, book II, Chapter V, §3]. One third being much less than the stochiometric 44% of weight loss for a pure limestone, considering even the stone to be completely dry. This difference in weight loss can be accepted if either some (hydraulic) impurity in the limestone are present or if some of the limestone hasn't been burned enough to be completely converted into quicklime.
2. Another reason could also be that the time span between the slaking and the use of the lime for the mortar is having an influence on how appropriate a lime is considered for mortars. As long as mortar is slaked and used within a week (up to 2 weeks at the maximum) the hydraulic lime component is still contributing to the binding and is not considered as a deficit in the binder. Calcination or burning a clayish limestone up to 900°C will result in the making of â-C_2S that takes a long time to set completely (Bertoldi, 1987)(Callebaut et al. 2000).
3. A third reason to doubt, is related to the previous one; if a part of the hydraulic fraction of the lime becomes an inert filler due to premature setting, the mortar composition can be adapted in the mixing faze to compensate this lack of (active) binder.

The above arguments are valid for lime mortar (for masonry) and are not necessary valid for the use of lime for fine renderings or for lime paints which might require other rheological properties.

Lime technology in medieval time

It might be considered a long step in time to go from Roman period to the medieval but from the period in between no much progress on (scientific) understanding on the use of lime can be reported. In our regions different illustrations and texts of that period have contributed to a better understanding of the way lime and lime mortar was used. For the illustrations we will refer to the publication in which they can be found instead of representing them here.

The technology of making lime did not considerably change until the eighteenth —nineteenth century. The poorly organised building industry and the supply of raw materials obliged the builders to look for their building materials in their immediate environment. This explains the variety of compositions in the mortars found through the chemical analysis of ancient mortars nowadays. Also the hydraulicity index[4] of the mortars analysed varies considerably. This index seems to be the most discriminative element in the comparison of different mortars analysed by chemical methods. This index reflects something of the practice in a way that the type of limestone and/or the use of artificial or natural pozzolana can be traced back.

A natural pozzolana used at that time in Belgium, the Netherlands and Germany was and still is named trass. Trass is a powdered tuff stone from the Rhine Valley; its quality depends on the composition of the raw material (N. 1967). As in the Roman period artificial pozzolana were mainly crushed ceramics (tiles, bricks, . . .). Natural hydraulic lime was available on the borders of the river Scheldt in the neighbourhood of Tournai. The stone of these geological layers has been used in Romanesque and early Gothic period almost everywhere it could be transported. Probably also the same limestone was transported for making lime. Recent research on a limited set of mortar samples of civil architecture in Tournai seems to indicate that, however close to the mentioned quarries, no hydraulic lime was used for masonry mortar (Callebaut 2000).

Composition of lime mortars based on chemical analyses.

Different analytical methods are being used for the identification of the composition of lime mortars. The following publications give relevant recent information on those techniques: (Van Balen e.a. 2000; Callebaut 2000; Callebaut e.a. 2001; Ellis 1999; Hughes and Cuthbert. 2000; Hughes e.a. 2001; Lindquist and Sandström. 2000; Martinet and Quenee. 1999; Mueller and Hansen. 2001; Prado e.a. 2001; Radonjic e.a. 2001; Schlütter e.a. 2001; Winnefeld and Knöfel. 2001).

Chemical analysis can help to compare mortars with each other and help to identify different building periods. It is the first method that has been used to analyse mortars with the intention to date them. In the beginning when Jedrezewska (Jedrzejewska 1960; Jedrzejewska 1967; Jedrzejewska 1981) started the research on chemical analyses it was hoped that this method would give an absolute date of mortar samples by identifying the evolution of the mortar composition with time. Today this is considered a unrealistic endeavour.

Chemical analysis can give some information on the composition of the mortar, although the exact composition can only be found when the raw material (lime, sand, . . .) are available. The dependence on the local available material makes this research very difficult.

The study of the grain size distribution of the sand can be helpful in identifying mortars, as it can help to identify the sand used for preparing the mortar.[5]

From the analyses of different mortars for rendering and masonry, Wisser (Wisser and Knöfel, 1988) found that the sand to lime ratio was higher then in Roman times. They found an average of 28.5 weight percentage lime in the mortars. Many other analyses seem to confirm this high lime content in our regions. Analyses carried out at the Laboratorium Reyntjens showed that the lime content of different samples from the Cathedral of Antwerp varied from 16% to 55%[6] (Van Balen and Van Gemert. 1990).

Due to the high amount of lime the question arose whether such a lime mortar could have been used without having problems with shrinkage (Wisser and Knöfel, 1988). The authors' conclusion was that they must have been slaking the lime with (wet) sand, which explains also the presence of the typical lime piths in the mortar. Slaking with sand necessitated less water and the shrinkage afterwards must have decreased.[7]

The dissertation of K. Callebaut exactly studied this assumptions and he has demonstrated that the slaking of lime with sand is feasible and corresponds

with the findings in ancient mortars. He also showed that this slaking technique results in a mortar with an acceptable higher binder content and a lower water demand (Callebaut 2000, 181)

Lime production and sale

Some aspects related to the production of lime mortar are illustrated in the works of F. Van Tyghem (Van Tyghem 1966), Binding and Nussbaum (1978) and Du Colombier (1953). They studied the medieval building practice through iconographical representations.

Lime production

During the Middle Ages two types of kilns were used: continuously and intermittent working kilns. In the intermittent kiln it took 3 to 4 days to heat the kiln and to allow it to cool enough to take out the burned limestone. This way of working corresponded very much with the description given by Cato. The continuously working kilns were used in the same way as in antiquity.

Before the sixteenth century very few limekilns had been depicted on paintings or drawings. More representations are known from the sixteenth century on. One of the oldest representation of a lime kiln can be found in a Sicilian mosaic from the 12th century in the Capella Palatina in Palermo (Van Tyghem 1966).

Limekilns were either built beside the river that was used to transport the limestone, as was the case for the Flanders' kiln represented on an engraving of the townscape seen from the other side of the Scheldt.[8] In the kiln at the border of the Scheldt in Antwerp probably limestone of the Tournai region must have been burned.

Limekilns were also built beside the great building sites or at places where limestone and/or fuel was available. Until the end of XIII° wood was primarily used as fuel. To burn lime, an important amount of wood, coal or peat was needed.[9] Due to a better energy balance the amount of coals in a continue kiln could be diminished with 20% (Davey 1961).

To produce 1 ton of lime the quantity of wood necessary corresponded with an oak of 46 cm in diameter and a length of 9 m, or two pine trees with the same dimensions. It is obvious that the consumption of such amounts of timber, not only for lime burning but also for brick firing caused problems of shortage[10] and therefore other sources were sought. More and more coal was used but this fuel produced significant air pollution. Therefore new regulations were issued at the beginning of the 14th century e.g. in London (Salzman refered to in (Davey 1961) to reduce the impact of air pollution on the population.

For the same reason the magistrate of Brussels issued some measures in 1415–1416, and in 1536 it was forbidden in Amsterdam to make or set up a limekiln within one mile of the town (Van De Walle 1959, 65).

In the Netherlands mainly seashells were used for producing lime, as there is almost no limestone source available, this was also the case in the 14th century. As a source of energy often peat was used in the lime kilns (Janse 1981).

Burning lime was a job for skilled workmen and the work continued over night as the kiln had to burn continuously. Therefore the lime-burners were paid well (Salzman 1965, 152). Carrying limestone and the lime was a job for unskilled workmen:

> Many persons were needed to make the kiln, charge and discharge the kiln, to guard the kiln and to watch the fire, as can be calculated from the achieved working days. In Wijk (The Netherlands) in 1345 during 4 weeks about 700 working days have been counted for men and women to carry; 160 working days were needed to prepare and shovel the lime. (Janse 1981, 165).

Lime trade

Medieval city councils were concerned about the quality of lime. In 1383 an inspection of production and the trade of lime was introduced. In 1531, only lime certified by the city council could be used (Van De Walle 1959, 65).

Rules of the «Bauhutte» in Prague stated that a master mason had to demonstrate to own 7 lime pits.[11] This was to guarantee the quality of the lime.

Even for warfare lime was an important «raw material», especially to construct fortifications. The story is known from Duke Willem II who prepared a battle in Friesland. He shipped out lime to construct compulsion fortifications in Friesland. He didn't succeed and came back with the shipped lime that was sold to the public (Janse 1981, 165).

From a study on the architecture of the Gothic Sint Kwinten church in Leuven (Cuypers 1958) we know

that in some cases the church fabric provided the lime to the mason and in some other cases in the same period, the mason of the vaults himself had to provide for the lime [from Namur or Fleurus].

Application of lime mortar.Use of lime mortar

Lime was mixed with sand and as such used as a mortar. Different types of tools were used.

A typical tool used to prepare lime mortar was the lime chopper to mix the sand and the lime and to crush the lime piths (Van De Walle 1959, 82). The lime shovel was used to shovel the lime from the pit to the lime 'sleeve» or basket, with in turn was used to carry the lime to the masons tub. To fill the lime basket at shoulder height it was placed on a tripod or tetra-pod (Du Colombier 1953, Fig. 35).

Different sources indicate that lime was sieved or poured through a great basket with holes (Van De Walle 1959, 82; Salzman 1967, 337) to take out the bigger pieces of burned limestone that probably were badly slaked.

Building and precautionary measures

Masons were divided into different categories. The two more important categories were the master-masons (they were also stone carvers) and the masons. The latter are only responsible for the placing of stones (Du Colombier 1953, 38). Master masons had to teach their apprentices the composition of mortar. The latter were divided in groups as: mortar 'makers', lime 'slakers' and plasterers (Janse 1965, 31). The preparation of mortar was the job of the less skilled workmen. Therefore they were paid as normal workmen (Salzman 1967, 153).

In the winter, masons couldn't work as such due to frost danger of the slow setting lime mortar. In contracts it was often stated which periods of the year allowed a mason to work.[12] To protect masonry against frost in winter it was covered with sod and/or straw and vaults[13] were covered with peat[14] (Janse 1965,.88). In winter the masons were involved in the carving of stone, as it happened in Köln in 1430 (Du Colombier 1953, 37).

Roman mortar in the Renaissance

The Roman mortar technology as described by Vitruvius is taken over in the books of Leone Battista Alberti (De re aedificatoria), Philibert de L'Orme (Ouvrages d'architecture, 1567), Andrea Palladio (Trattato d'Architettura, 1570) and Vincenzo Scamozzi (L'idea dell' Architettura Universale, 1615) (Ferraris 1968).

The influence of the setting on the building process in the Roman period is not well known. Vitruvius (Vitruvius, II° book, chapter IV) only stated that sea-sand slow down the drying process as well as the construction process. Therefore sea-sand can not be used for mortar to erect vaults.

On the other hand Alberti (De re aedificatoria, III° book, chapter 14) is more precise and writes that the building process had to be stopped from time to time to allow the mortar to dry properly.[15] Alberti describes how the centrings of vaults and arches have to be lowered down to guarantee a proportional and smooth setting of the masonry due to the plastic deformation of the mortar. This plastic deformation influences the stress distribution in the arch and in the vaults (Krauss s.d.; Fitchen 1981; Van Balen 1991; Van Balen 2002).

From a report of Raphael to Leo X «on the buildings of antiquity in Rome and the way the ground plans should be measured» of 1519[16] we know that a certain resistance raised against the burning of marble of buildings from antiquity to make lime. This indicates that the recuperation of marble was very usual not only to use it as such (Du Colombier 1953) but also to make lime out of it. The high cost of transport at that time certainly explains this practice.

We prefer to go to the 17th Century to report more progress on the understanding of the use of lime and its hardening.

Lime cycle according to Perrault at the end of the 17th century.

The comments of Perrault[17] on the writings of Vitruvius' Ten books on architecture give a good idea of the 17th century knowledge on the lime cycle.

Perraults' remarks on the theory of Vitruvius were based on the principles of the iatro-chemical range of thoughts.[18]

The loss of water by which, according to Vitruvius, the limestone loses its strength is, according to Perrault, due to the loss of volatile sulphuric salts (Sels volatiles et sulphurez) during the burning of limestone. Hardening occurs due to absorption (again) of those salts. The increase of strength by mixing lime with sand is due to the exchange of salts between the sand, the stones and the lime. Carbonation can take a long time, as a long time passes before the lime has absorbed all salts that have to return from the stones and the sand.

It is remarkable that he speaks about volatile salts that can be associated with something that has to come out of the air, but the explanation of the hardening refers to the uptake of salts from the stones and the sand.

A HANDBOOK IN PARIS AT THE END OF THE 18TH CENTURY.

In «Le guide de ceux qui veulent bâtir», from the architect N. Le Camus de Mézières (Le Camus De Mézières [1786] 1972) it is shown how, although the chemistry of the hydraulic reactions are known, alchemy inspired the way of working with lime (mortar):

> Une chaux qui est trop longtemps exposée à l'air ou dans un endroit humide s'évapore d'elle-même: le feu et les esprits s'en dissipent, elle se réduit en cendre et n'est d'aucun usage, c'est une chaux 'fusée'.

This handbook gives the best origin of limestone in the environment of Paris (Senlis stone is the best)(Le Camus De Mézières [1786] 1972, 86) and describes the kilns: to burn lime a kiln has to be made with an elliptic inner section (Le Camus De Mézières [1786] 1972, 88). Good limestone can be distinguished from others by the clear sound produced when two slabs are knocked against each other, by the strength and the homogenous milk-white colour. Good quality-limestone yields quicklime that produces twice the volume of lime putty. Lime improves when keeping it for a certain time before use (Le Camus De Mézières [1786] 1972, 87):

> «Il semble que les sels s'aident les uns et les autres; et en effet la chaux est d'autant meilleure qu'elle est plus anciennement éteinte: ne craignez donc pas d'en avoir grande provision du premier instant, exigez-le même de vos entrepreneurs.»

Sand may not be too fine because the mortar becomes to fat by which the contractor will use less lime and the mortar will become to sandy.[19]

Cement is, according to the author, a mixture of lime with crushed ceramics. Good burned clay, e.g. earthenware and tiles, gives the best link with lime (Le Camus De Mézières [1786] 1972, 91).

Mortar has to be made with one third of lime and two thirds of sand everything mixed up very well (« . . . bien broyer, corroyer avec le rabot . . . »). Not too much water may be added, what seems to be difficult (« . . . *vous aurez de la peine à faire valoir ce principe* . . . » (Le Camus De Mézières [1786] 1972, 93). The workability of the mortar depends not only on the amount of water but also on the degree of knocking of the mortar. Lime must be slaked at least a few days before use and must be prepared one day before.

Setting of the mortar can take some years and requires a little bit of humidity, mortar may not dry out as this slows down the hardening « . . . s'il (le mortier) n'étoit pas surpris par la hâle et par une sécheresse trop prompte, il lui faut des années pour se faire, se mûrir, devenir aussi dur que la pierre et s'identifier avec elle . . . » (Le Camus De Mézières [1786] 1972, 94).

The progress of the construction has to take into account the time needed for the setting of the mortar. Still according to «Guide de ceux qui veulent bâtir; . . . » iron bars can be putted beneath the lintels if there is no time to wait for the hardening (Le Camus De Mézières [1786] 1972, 117).

MODERN BINDING MATERIALS FOR MORTAR.

Discovery of the hydraulic reaction.

Many publications have well described the technological evolution caused by the discoveries of Smeaton and Vicat, and placed it in its historical context as (Guillerme 1986; Guillerme 1995)

Smeaton discovered the hydraulic reactions in 1756 searching for a way to make a water resistant lime. From the chemical analysis of the limestone used for the production of natural hydraulic lime he decided:

> the presence of clay in limestone is the most important, if not the only, decisive factor for the hydraulicity.

In 1812 Vicat proved that hydraulic properties were due to the burning together of lime(stone) end clay. Indeed, after de-hydration of the clay and the decomposition of the limestone, a reaction occurs between the quicklime (CaO), the siliceous oxides, the iron oxides and the aluminium oxides. Dependent on the amount of clay and the burning temperature, this reaction is more or less finished and thereof depends the degree of hydraulicity.

The works of Vicat are the basis of all further scientific work on hydraulicity of binders. The result he achieved with his production method is a product that could be placed in between lime hydrate and the actual portland cement. The amount of calcium oxides were so high that this cement had to be slaked. By this slaking calcium oxide has to be converted in calcium hydrate, but too much water had to be avoided, as the hydraulic components may not react with water.

The research methods used by Smeaton and Vicat are evidence of a new scientific understanding. After the philosophy of nature in antiquity (Vitruvius) and the iatro-chemical ideas (Perrault) modern science threw a new insigth on the principals of the hardening of lime and hydraulic limes. The understanding of the complete lime cycle was improved again.

Portland cement.

In 1824 Joseph Aspdin acquired a patent on cement, which he said becomes as hard as portland stone. L. C. Johnson (1835) discovered that the clinker produced by sintering the (hydraulic) lime gave better results when it was powdered. What we actually use as portland cement is the powdered clinker produced by firing the raw material, limestone and clay, to a temperature of 1450°C to which is added gypsum as a reaction retardant. Since the nineteenth century the production of the real Portland cement hasn't changed so much, although a variety of types and admixtures have found their way to the construction market. Scientific research has brought refinements to the production and increased the number of several types of cement for different applications.

In the nineteenth century Belgium was one of the most important producers of hydraulic lime. Limestone was exploited and burned in the region of Tournai. Various old kilns still testify this important industry (Chantry 1979). Today this sources of limestone is used for the production of Portland cement.

From the beginning of the twentieth century Portland cement started to become the most important binder for the fabrication of mortars in masonry and replaced the use of high calcium lime and hydraulic lime in Europe and the United States.

Prescriptions about the use of lime in 19th and 20th century.

A number of prescriptions of nineteenth and early twentieth century give an interesting picture of the use of lime as a binder for masonry mortar.

The Netherlands, in 1843

The Netherlands is known for its history of hydraulic engineering constructions in which they used a mixture of lime and trass. Trass was imported from Andernach in Germany at the border of the Rhine, near Koblenz, but so much associated with The Netherlands so that is was often called «Dutch trass». Dordrecht was an important trade centre of trass and the quality of this trass was controlled and inspected, for a long time, by official inspectors (N 1967).

In «Bouwkundig Magazijn of Schetsen voor Handwerklieden» (N. 1843) different compositions of mortars are given for masonry of different type. They were all based on the use of lime (made of shells or limestone), trass and sand. The amount of trass increased when the masonry mortar was more exposed to water.

The amount of lime (plus trass) to sand was about 1.5 to 2 parts of lime for every part of sand. This ratio is very high and the risk for shrinkage must have been great. We don't know how they managed to keep this under control.[20]

To stimulate carbonation it was advised to make the mortar with more sand in the fall and with more lime in the spring as the mortar had enough time to dry.

When lime was made with shells it was also advised to use more lime in the mortar in case lime made from limestone was used.

Belgium in 1869

From the reading of a handbook of 1869, edited in Mons (Devillez 1869), it becomes clear that the use of cement was much more important in Belgium than in The Netherlands. Here different binders were proposed: high calcium lime, hydraulic lime and cement. The carbonation was described here as a diffusion process that

> slowly progresses from the surface to the centre, as heat progresses in a mass that is heated at the outer side, . . .

Devillez also know that it is important to keep the walls humidified in which hydraulic limes are used. But regularly wetting of the masonry is

> also helpful for mortars with high calcium lime as fast drying can make it pulverised and humidity stimulate the action of carbon dioxide . . .

The sand of lime mortar with high calcium lime may not be to fine to stimulate the diffusion of carbon dioxide. Bastard mortar is described here to be a lime mortar to which cement or pozzolanas are added.

Germany in 1880–1890

In chapter 3 «Die Mörtel und ihre Grundstoffe.» of «Allgemeine Hochbaukunde, des Handbuches des Architektur, 1ste deel, 1ste Band, Die Technik der wichtiger Baustoffe» (Hauenschild 1883) different phases in the increase of strength are described:

> Lime mortar first dries out and strength starts to increase. Afterwards carbonation starts and calcium carbonate crystals are formed.

The porosity of the bricks defines also the amount of water to be added to the mortar: the more porous, the more water has to be added. The author remarks that with the water little lime particles are transported to the contact zone between the mortar and the bricks. This increases the adhesion between both.

Mortars with a low hydraulicity lime and «poor» lime can be slaked with wet sand. This method was much used by the French and the Italians in their hydraulic constructions. Lime cement mortar was the type of masonry mortar used most often. According to Dyckerhoff (Hauenschild 1883) masonry mortars with Portland cement, lime putty and sand have better water resistance, adhesion and are stronger then mortars with equal parts of Portland cement and sand.

The third chapter «Constructions-Elemente in Stein.» from the third part of «Des Handbuches der Architektur» (MARX Erwin. 1886) is also referring to the role of sand: porosity that must allow carbon dioxide to penetrate in the mortar and to induce the carbonation. Sand also provides the surface where calcium carbonate crystals can deposit. Without sand, lime is no adhesive but only a stress distributer.

Lime producers in Belgium at the beginning of the twentieth century.

A technical note in «Bulletin des Métiers et d'Art» of 1909–1910 (N., 1909), gives information about the limestone quarries exploited at that time and the type of lime that can be made with them:[21] «high calcium lime», «weakly hydraulic lime», «moderately hydraulic lime», «hydraulic lime» and «strongly hydraulic lime»

This historical description is ends with the loss of interest in lime after the First World War and the beginning of what we could call modernity in engineering and material sciences.

In Belgium, the fact that the raw materials once used for the production of hydraulic lime [that on its turn was exported to adjacent countries and over the Atlantic] is now exclusively used for the production of cement and the fact that the term hydraulic lime seems to be forgotten, may be seen significant for the trend.

The growing interest in lime today has been boosted by the field of architectural conservation. This is partly due to the many damages noticed in historic buildings due to the use of inappropriate cement mortars in restorations. On itself this is a complex field of research dealt with by different research teams.

Conclusion

The empirically developed technology of using lime expressed in terms of in field application hasn't probably changed so much since the technology was widely established and understood by the Romans. The understanding of the mechanisms responsible for

the production, the hardening, and the setting of lime mortar for different applications, has changed together with the evolution of scientific understanding and human's perception of the earth.

An overview of this evolution has been given referring to common lime practice that today is often forgotten. Precious advice on the use of lime for mortar can be thus collected that serves today's research community to look for sustainable building practices and compatible maintenance and repair techniques in conservation.

NOTES

1. Many thanks to Eric Bruehl, research assistant at Getty Conservation for the revision of the English.
2. This paper compiles information from the historical part of the PhD of the author (Van Balen 1991, Ch.2) written in Dutch and never translated into English. Often requests have been received to give distribute its content as to allow scholars to find their way to the content of the work and to the references on the topic. Within the framework of this conference the information was updated. Within the time given in a current sabbatical leave at the Getty Conservation Institute in Los Angeles, other aspect on lime mortar carbonation and its effect on historic structures are being updated and will be published.
3. More recent research in the «New World» seems to indicate that lime can be produced in open fires (Sickels 1996).
4. The hydraulicity index has been defined by Vicat to express to what extent a binder hardens with water. He proved that the presence of calcium silicates and calcium aluminates are determinant for the hydraulicity and defined the index as the ratio of the acids (SiO_2, Al_2O_3 and Fe_2O_3) to the bases (CaO en MgO). The hydraulicity index has no absolute value as it doesn't make the difference between Al_2O_3 and SiO_2, nor between MgO en CaO; it further doesn't give any indication of the bond between the different components which is of great importance to the hydraulicity.
5. This method has also been used by Frizot (Frizot M. 1975; Frizot M. 1981) to characterise Roman mortars. The method can only be used when the sand is siliceous and contains no limestone, as it will be dissolved by the chloric acid.
6. The average of 19 samples gave 30.03% with a standard deviation of 11.42%. From the results of the chemical analyses 8 different groups of mortar could be identified of which 5 groups had more than 1 sample. Grouping of mortars was accomplished taking into consideration different criteria such as: lime content, grain size distribution, hydraulicity index, difference in chemical composition of the oxides and the magnesium content.
7. This method of slaking has been used by the late Prof. R.M. Lemaire for all restoration works after 1952, e.g. at the Great Beguinage in Leuven and the church of Tourinnes-la-Grosse. A mixture of lime and wet sand was kept apart for one year before use. It was then certain that all quicklime was slaked <oral communication from R.M. Lemaire (02/91).
8. Lime kiln: view on the roadstead of Antwerp, 1515; Prentenkabinet Antwerpen; «This is the lime kiln of Flanders» (Van Tyghem 1966, fig.197).
9. According to Burnell —quoted in (Davey 1961)— the amount of fuel to burn 35 cubic feet of lime (about 1 ton) in an intermittent kiln was: 60 cubic feet of oak, or 17 cubic feet of pine, or 9 cubic feet of coal, or 117 cubic feet of peat.
10. An example is known of a claim dating from 1275 regarding the use of 500 oaks from the Wellington forest (Great-Britain) for the limekilns of the king (Davey.1961, 101).
11. Oral communication given by Prof. R.M. Lemaire (†), referring to the still existing copies of the rules of the Prague «Bauhütte». (06/91)
12. At the occasion of the construction of «Walberswick Church» (Suffolk) in 1425: «*Two mason's undertake to build a tower, . . . They shall work yearly from Lady Day to Michaelmas, 'except the first year' (when, presumably, they will be cutting the stone, which could be done at any season)* . . . » (Salzman 1967, p.499).
13. Although vaults were generally built only after the construction of the roof it was considered necessary to cover the vaults to protect them against frost.
14. A clear idea of the protection measures against the frost degradation of masonry can be found in the expenses for the construction of the St. Pieters church in Leiden in 1399. 30 feet reed, 7 ships of peat have been purchased to protect the construction and 1600 sods to put on top of the masonry. This material had to protect newly built walls and pillars against the destructive effect of frost before the construction of the protective roof. It was written down that Jan the «master builder» had to carry peat onto the vaults. In 1625–1627 the expenses of the O.L.Vrouw-over-de-Dijle church in Mechelen mention the costs for a thatcher to cover natural stone and bricks (Janse 1965).
15. An important aspect of the setting and carbonation of lime mortar is quoted here. The theoretical background is still the same as this used by the Romans.
16. Based on the manuscript of Münich, edited by J.D. Passavant(?) in: Raphael von Urbino und sein Vater Giovanni Santi (Leipzig, 1839) quoted in (Choay F. s.d.)

17. (Perrault [1673] 1979), Chapter V. De la chaux & quelle est la meilleure pierre dont elle se fait
18. This is the name given to the era of material (science) that started during the first half of the sixteenth century. Paracelsus was one of the forerunners of this theory. According to this theory all material was composed of three elements: mercury, sulphur and salt. Ontologically speaking, mercury represents the active spirituality, salt represents the passive corporality and sulphur is the link between both (Dijksterhuis 1980, 308).
19. It is good to mention here the complete title of the book of Le Camus de Mézières: 'Le guide de ceux qui veulent bâtir; ouvrage dans lequel on donne les renseignements nécéssaires pour se conduire lors de la construction, *et prévenir les fraudes qui peuvent s'y glisser»* (author's emphasis).
20. Compare with the remarks made by Wisser on the method of mixing high amount of lime with sand (Wisser and Knoefel 1988) as we discussed above.
21. High calcium lime: Rhisne and environment, Arquennes, Ecausinnes, Soignies, Ath (H.), Boussu (H.), Cerfontaine (N.), Ciney (H.), Forries (L.), La Buissière (H.), Maffles (H.), Rochefort (N.), Wépion (N.), Visé (L.), . . . ; Weakly hydraulic lime: Barvaux (L.), and the environment of Durbuy and in Blaton (H.); Moderately hydraulic lime: Altert (L.), Bouvignes (N.), Couvin (N.), Fosses (N.), Horion (L.), Huy (L.), Lavoir (L.), Muno (L.); Hydraulic lime: Antoing (H.), Baelen-lez-Limbourg (L.), Basècle (H.), Calonne (H.), Chokier (L.), Fovrières (L.), Frasnes (N.), Heppignies (H.), Hollogne-aux-Pierres (L.), La Buissière (H.), Wazy (N.), Mevergnies (H.), Oret (N.), Rhisne (N.), Rossignol (L.), Soy (L.), Viesville (H.), . . . ; Strongly hydraulic lime: Chaudfontaine (L.), Chercq (H.), Nismes (H.), Solre-Sambre (N.), Tournai (H.), Vaulx (H.), Antoing («chaux de Coucou»).

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From Nieuport to Magnel: An institutional history of building science in Belgium, 1780–1930

Dirk Van de Vijver

While general overviews of the history of building mechanics are well established,[2] Belgium still lacks a study of the concrete local appropriation, diffusion and application of this scientific discipline.[3] This history of the reception and local development of the building sciences, considered here in their triple nature of the calculus of structures, the testing of materials and their technological applications —a complementary history to the instauration, rise and institutionalisation of the civil engineer—, considers public, scientific, normative and educational institutions, scholars and manuals as their principal actors.

The scope of current historiography —limited to a few «key»— figures like Vierendeel (Lederer 1970; *Arthur Vierendeel* 1989) and the use of new materials like steel (Baele and De Herdt 1983) or concrete[4] — forced us to undertake substantial research of institutional and biographical nature[5] and to elaborate a key research tool: a bibliography of Belgian technical writings on building.[6] The exhaustive list with references to library copies creates a virtual library which responds more to the needs of the historian than the remaining collections of libraries of educational and research institutions.[7]

The emergence of a new architect and a new engineer (1750–1830)[8]

Parallel with the elaboration of a network of roads and canals in order to fully benefit economically from the strategic position of the Southern Low Countries between the Canal and the German hinterland, the local and central governments of the Austrian Netherlands created civil administrations for public (especially hydraulic) works. In this way, the civil government regained independence from the corps of military engineers. The States of Flanders created a two headed professional administration of Public Works (an architect and an engineer) in 1755; the central government created the *Jointe des Eaux* (1772) with a *Corps* and an *Ecole hydraulique* (1774) with seat in Brussels. The programme of this (first state civil engineering) school offered a preparation to the application of hydraulics in practice. Also around the same years, in 1778, Jean-Joseph Mottin taught architecture as applied mechanics at the old University of Leuven.[9]

In 1772, the *Académie royale et impériale de Bruxelles* was founded by the government of the Austrian Netherlands as a state research institute with a double mission: to support the economic development by the exploitation of the natural resources and technical sciences (the «classe physique») and to write the history of the Austrian Netherlands («classe historique»). In this local version of the French Academy of Science the technical aspects of building were the object of attention: building materials (mortar, brick) were tested, fireproof constructions were studied (Mann 1778), the hydrographical situation of the country was evaluated[10] and hydraulic inventions were

certified. The knowledge of higher mathematics by their members, especially by the military engineer Charles-François le Preud'Homme de Nieuport (1746–1827), also permitted to treat the problems of the calculus of vaults with mathematical tools evoked by Euler, Krafft, Bossut and Jakob Bernouilly (De Nieuport 1781; Radelet-De Grave 1995). De Nieuport also formulated a public prize question relating to the calculus of an isostatic supported beam. The unsatisfying answers showed the isolated position of the Academy in these matters and the growing gap between traditional artisan knowledge and the new «mathematical» engineering science.

By publishing the work of her members and the prize winning responses, the Theresian academy broke also with another tradition of the Southern Low Countries: the oral (and manuscript) transmission of technical knowledge. Even if hydraulic and engineering realisations could rival with those of the Republic, local specialised libraries[11] must rely on the lavishly illustrated Dutch works on hydraulic machinery (Van der Horst and Poley 1736–1737) or the French resumés of the available technical knowledge (Bélidor 1729, Bélidor 1737–1753) to fill the engineering department.

The annexation of the Belgian departments by the French submitted public architecture and infrastructure works to the competence of French administrations, populated by French architects and engineers, respectively the *Conseil des Bâtiments civils* and the *Corps des Ponts et Chaussées*. The construction in Antwerp of the most important marine arsenal of the French Empire (Lombaerde 1987; Lombaerde 1989; Lombaerde 1992) put its stamp upon the writings of Sganzin, who directed the works, and of Louis-Charles Boistard (Boistard 1822). The French mining engineer, Alexandre Miché, stated in Mons, reworked and published the Bullet-manual (Miché 1812).

In the beginning of the 19th century a new engineering elite emerged (Van de Vijver 1993). As the Southern Low Countries were incorporated in the French Empire, young Belgian students were formed at the newly founded *Ecole polytechnique* and the subsequent *Ecoles d'applications*. Forced to return after the treaty of Vienna (1815), these polytechnicians of «Belgian» origin filled the «southern» vacancies of the engineering administration of the new Kingdom of the Netherlands (1815–1830), especially of the newly established *Corps van Waterstaat en Openbare Werken* (1818–), modelled on the French *Corps des Ponts et Chaussées* but with addition of the competence of the French *Conseil des Bâtiments civils*. Polytechnicians of French origin immigrated to the new Kingdom and were employed by *Waterstaat* or at the new Universities (Ghent, Liège, Leuven). This new generation with an ideal (French) scientific and technical background (taught by Durand, Sganzin, ...) filled easily the gap created by the departure of the French *Corps des Ponts et Chaussées*, became also dominant in the field of military engineering and ambitioned careers in the exact and applied sciences at the universities. The remarkable presence of newly constructed «Belgian» metal bridges, canals and sluices reported by Brisson (Brisson 1821–1825), or the detailed documenting of these technical realisations by the American engineer Loami Baldwin jr in his *Engineering diary* of 1823[12] is therefore not surprising. Nor was the formation — a polytechnical one— of the author of a mémoir presented to the Academy on the hydraulic qualities of local chalk (Cauchy 1827) a «hazard».

In the same period (1750–1830), the architecture of the Southern Netherlands was submitted to a parallel evolution: the emancipation of the architect. A formation based on drawing (after models and programmes) in the local drawing schools (the so-called academies) complemented the practical formation in the guild, and created a learned architectural culture (based on Vignola, Jacques-François Blondel and Jean-François de Neufforge). With the arrival of a new generation of French educated architects at the *Ecole spéciale d'Architecture* in the Dutch epoch (1815–1830), the academic formation was also to include the Beaux-Arts composition technique (Van de Vijver 1998). New attention was given to the more technical aspects of building in the local academies. A new translation of Vitruvius, published in Brussels (De Bioul 1819) and a publication of the most important buildings of the new kingdom (Goetghebuer 1827; Van de Vijver 2000a) underlined the emergence of a new architect. The hierarchic structure of the course of construction taught at the *Musée des Sciences et des Lettres de Bruxelles* by the polytechnician Nicolas Roget (1790–1865) («l'exposition des qualités des matériaux ... , les réunir pour composer les élémens

des edifices . . . , composer avec ces élémens les edifices mêmes») established an ideal base for both architect and engineer (Roget 1829, 79).

The Belgian conquest of the building sciences

With the institutionalisation of the new Belgian state of 1830, a new *Corps des Ponts et Chaussées* was erected. This was complemented by a long expected polytechnical school at the State University of Ghent (the *Ecole Spéciale* for the administration of Public Works, 1835) —a state school for Mining was confided to the University of Liège—and an own periodical: *Les Annales des Travaux Publics de Belgique* (from 1843 onwards). The continuity was insured by the reemployment in the new engineering corps of the polytechnicians of the southern divisions of *Waterstaat*. The *Annales . . .*, composed by and for the *Corps . . .*, published the results of recent research and practice, constructing in this way a shared knowledge of local building materials (due to new and systematic testing campaigns), building techniques and calculus methods.

If the programme of the Ghent *Ecole préparatoire* and the *Ecole spéciale* included evidently the engineering courses, as for instance analytical mechanics (taught by Jean-Alexis Timmermans (1801–1864) from 1835 to 1864), mathematics and mechanics were also taught in the science programme of the three universities Ghent (Timmermans), Liège (Jean-Baptiste Brasseur (1802–1868), who also taught in the *Ecole des mines* and was renown for his theoretical approach) and Leuven (Gaspar-Michel Pagani (1796–1855)).

However, the Corps of military engineers played also a leading role in the production of technical texts. Remy Depuydt (1789–1844) republished the *Mémorial de l'officier du genie* (Depuydt 1844) and Armand Demanet (1808–1865) published the text of his *Cours de construction* (Demanet 1850), taught at the Brussels *Ecole militaire* from 1843 untill 1847. The latter was the first manual (including knowledge of local materials, structural theory and practice) specifically applied to the Belgian situation. The presence at the end of the second volume of the in 1849 adopted building specifications for the Ministery of War —also by Demanet's hand— places this manual in the French tradition of Bullet and Rondelet.[13] Both French manuals received Belgian updated editions. We mentioned already Miche's Bullet; Rondelet's annotated treatise was published in Brussels (Blouet 1848–1851). But also Sganzin's manual became popular (Sganzin 1839, Sganzin 1840–1844, Sganzin 1867), the last edition was annotated by E. Roffiaen, Demanet's successor at the Military School.

Besides these clear French references, the Belgian engineering world also kept tight relations with England. In 1850 for instance, the translation of Henri Law's *The rudiments of civil engineering* was translated as a *Manuel pratique de construction* (applied statics) in the series *Bibliothèque industrielle supporté par le gouvernement belge* (Law 1850). Already in the Kingdom of the Netherlands (1815–1830), Charles Dupin's technical investigation of British engineering contributions (roads, railways, bridges and steam engines) received a Brussels' edition (Dupin 1826). Personal voyages and public missions to England informed architects and engineers on matters of technical progress as gas lighting (Louis Roelandt), hygiene (Remont 1850, Remont 1853) and railways (Brees 1841). Belgium followed Britain's great example by introducing the first public railway (1835) on the Continent and realising one of the most dense railway networks of the Continent (if considered for instance in 1928).[14]

Another consumer of the Belgian iron industry was found in the development of metal carpentry for large span constructions —influenced both by French (Emy 1842; Polenceau) and English examples— for the new typologies of 19th century industrial society: railway stations (Antwerp, 1895–1898), exchange halls (eng. Marcellis in Antwerp, 1852), churches (Demanet 1847), green houses (arch. Ballat in Laeken, 1870). It is hardly surprising then, that the influential Dechamps' *Principes de la construction des charpentes métalliques* was written by the professor in industrial architecture at the Mining School of the University of Liège (Dechamps 1898).

Towards a Belgian contribution

The mathematical culture at the Ghent University, especially the research of Jules Massau on the graphic integration and the method of characteristics, contributed to the practical solution of numerous

problems. In 1880, graphical statics became an official part of the programme. However, the stress on mathematics and scientific rigour considered essential at an academic level (consider for instance the courses of Vierendeel, Magnel, Baes)[15] was not an option for the technical schools aiming at the artisan and technician: they had to develop their own, and often very successful, manuals on the resistance of materials and the calculus of structures. The success of such manuals like Louis Aerts's *Eléments pratiques de la résistance des matériaux à l'usage des ingénieurs, conducteurs des ponts et chaussées, architectes, conducteurs des travaux, élèves des académies des beaux-arts et des écoles industrielles* (Aerts 1886), proves the great stimuli of those works to the diffusion and vulgarisation of this knowledge. The rapid growth of *vademeca* or *aide-de-mémoires* with an always growing number of formulae, tables and abaci needed in daily construction practice (Moerman 1874; Hoyoux 1891; De Koninckx 1900; Nachtegal 1911a) are addressed to the same public. The *Agenda du bâtiment* by A. Nachtegal, a «chef de bureau d'études» and teacher at the «écoles industrielles d'Houdeng-Aimeries et de Tubize» became a long lasting success and was published from 1911 till 1969 (Nachtegal 1911b).

However, the greatest innovation in metal construction came from outside the three-poled Belgian academic engineering world (Ghent, Brussels and Liège) drawn above. In 1864, the *Speciale Scholen* were erected in Leuven (Vierendeel (1851–1934)) and in 1879 followed the *Ecole polytechnique* at the University of Brussels (Lucien Anspach (1857–1915)); in 1925 the University of Liège received a department of Civil Engineering due to the Dutchifying of the Ghent State University and the funding by the *Compagnie internationale des Pieux Frankignoul* — another Belgian concrete success story invented in 1908 and registered in 1911 (Baes 1930, 675–682). Arthur Vierendeel, whose motto was «l'ingénieur doit sentir d'abord, calculer ensuite», shocked the academic establishment with an «unorthodox» truss without cross-bar-reinforcement, «le poutre Vierendeel» (1896), where the canonical static triangles are absent. Approximations and confronting tests results permitted Vierendeel to present a calculus method, wich together with successful constructions, constituted the beginning of a flourishing international career for the Vierendeel-truss.[16]

For private works the engineer/architect/contractor, not obstructed by government regulation, could experiment in Belgium within the boarders of his personal legal responsibility. (Only the departments of War, Public Works and State Railways had stated type specifications). Therefore, the marriage between concrete and steel was consummated by a wide range of patents and systems, dominated however by the Hennebique system (Christophe 1899; Dumas 1902; Baes 1930). François Hennebique (1842–1921) started his career in Belgium with the construction of fireproof floors of the villa Madoux at Lombartsyde (1883–1884). He patented his «poutre en béton armé» in 1892. The engineering bureau in Brussels, where he started his world conquest, stayed active, even after the move of the office seat to Paris in 1899. Although the system Hennebique lacked rigorous calculus methods, the introduction of numerique elements based on experiments permitted the realization of vast and audacious constructions. Even if the chapter «fer et ciment» of Vierendeel's *La construction architecturale en fer, fonte et acier* (1896) constituted the first Belgian work that discussed the calculus of «ciment armée», Paul Christophe's *Le béton armé et ses applications* (1899) was the crucial step in documenting this new construction method; he also proposed a straight and simple calculus method which became classic.

As chief architect of the Belgian State Railways, an institution which already used the Hennebique system in an early stage (at Chimay in 1894), Léon Cosyn (1871–1914) published practical treatises on reinforced concrete (Cosyn 1911, Cosyn 1914), reducing with numerous abaci and tables the calculus method adopted by his administration: the prescriptions of the French ministry regarding «béton armé» of 1906. Belgian guidelines for the calculus of reinforced concrete date only from later on: those of the Ministry of Public Works and of the *Association belge de Standardisation* (founded in 1919) date from 1923. These regulations stimulated the development of laboratories for testing and control. Belgium disposed of one laboratory in Mechelen (at the Arsenal, conducted by Emile Camerman), one in Brussels (at the *Ecole militaire*, founded in 1913 and conducted by Rabozée), one in Ghent (the *Laboratoire du béton armé* of professor Gustave Magnel (1889–1955), created in 1925 by the State Railways and integrated in 1930 in the Ghent

university), and four at the University of Brussels (those of professor Dustin and of professor Louis Baes, both founded in 1924, the laboratory of the *Groupement professionnel des fabricants de ciment Portland artificial*, founded in 1926 and conducted by professor Dutron, and the *Office de contrôle et de recherches expérimentales concernant l'art de construire* of the *Société centrale d'architecture de Belgique*, founded in 1930), the *Centre d'essais et d'information of the Groupement professional des fabricants de ciments de laitier* (conducted by Magnel, 1925) and that at the university of Liège (1930 F. Campus).

The calculus of reinforced concrete was carefully introduced in the courses of the *Ecole militaire* (by Rabozée in 1899) and of the universities of Bruxelles (by Vandrunen in 1900), Ghent (by Keelhof in 1904), Leuven (by Vierendeel in 1905–1908) and Liège (Deschamps). But only in 1920 a (then facultative) practical course on the calculus of reinforced concrete was taught at the Ghent University by Gustave Magnel. The very successful manual (Magnel 1923–1924) received a fourth volume in 1948 consecrated on pre-stressed concrete (Magnel 1948).

Conclusion

In 1930, 150 years after his first application of higher mathematics on a construction problem, the institutionalisation of the new discipline (building sciences) and the new profession (the civil engineer) seems complete: both the discipline and the profession became crucial and indispensable for the construction of the built environment. At that time, Belgium had the highest density of railways and Hennebique system buildings, counted five chairs of building mechanics at an academic level with their related societies of graduates, publishes —often in collaboration with Parisian editors— his own manuals and reviews (*Les Annales des Travaux Publics de Belgique* and *La Technique des travaux* besides the periodicals of the ancient student associations of the engineering schools), and celebrated the centennial of Belgium's independence by receiving at Liège both the *First international congress on concrete and reinforced concrete*[17] and the *International congress for metallic structures.*

Notes

1. This is the first presentation of an ambitious long-term research project developed and stimulated by complementary (and funded) research projects on the influence of French architecture on the Southern Low Countries 1750–1830 (PhD, K.U.Leuven 2000), the emergence of the «new» architect and engineer 1750–1830 (F.W.O. G.0416.98, 1998–2001) and the building site of public works in Belgium 1750–1880 (F.W.O. G.0272.02, 2002–2005). It implies an exhaustive bibliography of Belgian technical writings on construction (manuals, periodicals, legislation . . .), and complementary research on scientific and educational programmes, institutions and protagonists.
2. Timoshenko 1953; Straub 1975; Dugas 1988; Szabo 1987; Benvenuto 1991; Guillerme 1995.
3. For Germany for instance, see the studies by Kurrer: Kurrer 1987, Kurrer 1988, Kurrer 1995.
4. Baes 1930. For the Hennebique enterprise, based in Belgium in the starting phase, see for instance: Delhumeau 1999; Delhumeau et al. 1993; Delhumeau 1992; Cusack 1984–1985.
5. For the history of the Ministry of Public Works and the Corps of state engineers in Belgium see: De Brabandere 1930; Watelet 1987; Velle 1991. For the history of architectural education: Verpoest 1984; Van de Vijver 2000b, 56–58, 60–62, 299–306. For the history of technical education see D'Hoker 1980. For the history of university engineering education see Verpoest 1989 (University of Leuven); *150 jaar ingenieursopleiding* 1986 (University of Ghent); Campus and Massonnet 1981 (Université de Liège); Van Drunen 1925 (Université Libre de Bruxelles).
6. The Belgian bibliography (1875–1974) was complemented by the catalogues of the university libraries of Leuven (Katholieke Universiteit Leuven) and Ghent (Universiteit Gent), and —for earlier literature— by our own research on Belgian architectural publications of the period (1750–1830): Van de Vijver 1997; Van de Vijver 2000b, 257–290.
7. To keep only the most recent edition of a manual was a common library policy.
8. See Van de Vijver 2000b and the forthcoming catalogue of the exposition *Ingenieurs en architecten op de drempel van de nieuwe tijd (1750–1830),* K.U.Leuven, spring 2003.
9. Université Catholique de Louvain, Archives, C.151.
10. Royal Library Brussels, ms. II.2136–2137. A.T. Mann, *Mémoire sur les lois du mouvement des fleuves, et sur la quantité der leur penten, en particulier des rivières et canaux de la Flandre; d'où l'on déduit une méthode générale et très facile de niveler tout ce pays; on y détermine la profondeur que doivent avoir les canaux et*

les écluses, et on indique plusieurs nouveaux moyens d'obtenir un parfait écoulement des eaux dont les basse terres de la Flandre sont inondées tous les hivers, 1774.

11. See our forthcoming study on libraries of architects, engineers and surveyors in the Southern Netherlands (1750–1830) to be published by the Royal Flemish Academy of Belgium for Sciences and the Arts.
12. American Philosophical Society, Mss. BB 189.
13. The following civil construction manuals belong to the same tradition: Launoy 1910; Francken 1911; Combaz 1895–s.d.
14. Lamalle 1930. The rapid expansion evoked an even passionate discourse in defence of the waterways by the head of the Belgian *Corps des Ponts et Chaussées*, Jean-Baptiste Vifquain (Vifquain 1842)
15. Vierendeel for instance states in the *Préface* of his *Cours de stabilité*: «Les mathématiques constituent le principal outil des sciences techniques modernes, et l'ingénieur vraiment digne de ce nom doit les posséder de façon très sérieuse ou sinon il se condamne à ne pas comprendre les raisons intimes des faits de statique et de dynamique qui constituent l'infrastructure des phénomènes et se trouvera très empêché dans les applications pratiques à en tirer; toutefois, il ne faut pas abuser des mathématiques, . . . » (Vierendeel 1931, 5).
16. *Arthur Vierendeel* 1989; Vierendeel 1920; for the calculus see also: Magnel 1934.
17. 585 participants from 48 different countries communicated 191 mémoirs.

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The use of dolomitic lime in historical buildings: History, technology and science

Rita Vecchiattini

The use of dolomitic limestone in lime production is historically well known in the north and south of Italy but it is also documented in France, Germany and United Kingdom, especially between the XVI and the XVII century.

This contribution intends to consider such material from three different points of view: the historical one, through the study of archive documents, treatises and manuals; the technological one, through the analysis of the still existing buildings as well as the production cycle; the scientific one, carrying out a research into the parameters that allow to expound the excellent result for ages of the mortar produced with the employment of such lime.

These three aspects, one to each other strictly connected, aid to reach a more complete knowledge about one of the most used materials in ancient buildings.

Archive documents and ancient manuals offer some information concerning typical usages in different areas, giving a general, even if incomplete, picture of production techniques that often were handed on orally and left to the craftsmen. The early technical-scientific publications dealing with this subject date back to the beginning of the nineteen century, when the scientific study of the building materials carried out methodically imposed itself. Such contributions are particularly interesting because the authors still keep in their minds the data provided from the experience. Stopping for a moment to consider the composition of the primary product, we can notice that an apparent discordance exists between practice in the pre-industrial era, result of centuries of empirics based improvement, handed on by word of mouth or at most by manuals and treatises of that time, and technical knowledge of the industrial era, based on behavioural observations and subject of specific analytic publications. In fact while in the past they considered useful, if not even necessary, the presence of suitable quantities of magnesium in the mixtures of mortars, instead in the last century the utilisation of such binder has been dropped because considered of inferior quality.

But the resistance and durability that magnesic mortars, in their different utilisation, have offered against physical and chemical agents of decay are the silent evidences of the performance they can offer, enabling to doubt all theories about binders from Louis Vicat on.

At this point science become absolutely necessary to give answer to questions that take root in the history of masonry. On this subject some of the early encouraging results of the scientific research will be enunciate.

Introduction

Lime is undoubtedly one of the materials most used in the history of building, both in bedding and lining mortars and in concrete imitating stone. It was widely used from the 3rd century BC[1] to the start of the

twentieth century, after which lime was gradually replaced by cement, in the conviction that the «new» material was better than the old in every respect. Actually, restoration experience has shown that, apart from aesthetic problems, specific physical characteristics of cement[2] do not make it compatible with lime-based structures and linings.

Today lime is once again present on the market, to satisfy the requirements of people working in the restoration field, who are continually in search of products respecting the theorised criteria of compatibility and reversibility. However, it does not seem that the lime produced and cast today is able to provide objects that are as efficient and resistant as the majority of the old ones were. During the decades it took for people to become certain that in pre-industrial construction it was not advisable to use cement, except for structural purposes, know-how referring to the production and employment of lime was irremediably lost. Hence architects and restorers are now concentrating their attention more and more on historic mortars, both to copy their recipes in order to solve design problems, and to study and characterise them simply in order to know more about them.

The present paper fits into this broad panorama of studies, since it looks in some depth at a particular type of lime, dolomitic, deriving from the decomposition of dolomite limestone, a rock constituted by a double carbonate of calcium and magnesium[3] $CaMg(CO_3)_2$. It appears interesting to analyse it since the use of this rock for the production of lime, now abandoned —although dolomitic limestone constitutes more than 50% of the carbonates on earth— was historically very common in the North and South of Italy but is also documented in Spain, France, Germany and England (Newton 1987; Manzano et al. 2000), above all from the 16th to the 17th centuries. Indeed, numerous analyses, aiming above all at characterising mortars present in historic buildings, bear witness to the use of dolomitic lime even where this was not the only material available, nor even the most convenient to use. This observation, together with the finding of archive documents (Vecchiattini 1998; Fieni 2000) specifically requesting lime from dolomitic limestone quarries, and the empirical datum that dolomitic limestone-based mortars do very well in the «test of time», makes it possible to consider the choice of this material one made in full awareness and not by chance, that is to say one due to convenience or to incapacity of operators to make the right selection.

Interesting and revealing, regarding the capacity to choose binders, is the case of the celebrated Porta Bozzolo villa at Casalzuigno (Varese province) (Bassani e Cassani 1994; Fieni 1995, 64–68), in which the lining mortars were done with care and attention varying with the importance of the rooms, but always with magnesic limestone from Valcuvia. What is particularly striking is that the variation in the quantity of magnesium in the binders used indicates the employment of limestone coming from the decomposition of both magnesic calcareous rock and dolomite. Specifically, the magnesium content is higher in the outer layers, which are more exposed, than in the underlying ones, which are protected.

So why was such a resistant and widely used material considered inferior, starting from the first decades of the twentieth century, and gradually forgotten? It was in order to answer this question that an ongoing study on this theme was begun, with the aim not only of providing as much knowledge as possible on dolomitic limestone, but also of evaluating the possibility of bringing it back into building practice.

It is now clear that there is an apparent discordance between know-how in the pre-industrial epoch, the outcome of centuries of honing based on empirical criteria handed down orally or at most through the manuals of the day, and the theoretical knowledge of the industrial era, based on behavioural observations and dealt with in specific analytic publications. The art of producing limestone greatly changed during the last century, which was profoundly marked by a generalised technological renewal that was translated into the employment of raw materials which were more and more carefully chosen and of hi-tech equipment able to satisfy the needs of a big number of consumers, who were often not very qualified and were further and further away from the know-how of the past. Recovering the ways in which, in the past, traditional binders were produced and cast means re-examining and interpreting old «know-how» and also reconstructing, with the help of science, the route taken in the past to produce and cast materials that, as the facts demonstrate, gave better results than present-day ones. Hence in the framework of research applied to the conservation of the cultural heritage, it

is necessary to blend history and science, and to approach the theme from different points of view.

THE CONTRIBUTION OF HISTORY

The study of the written sources is fundamental to knowledge of some aspects of the production and employment of lime, which otherwise it would be impossible to recreate: archive documents and old manuals furnish notices on the specific customs of the various geographical areas, helping to build up a general though incomplete picture of operative practice, mostly left in the hands of craftsmen and handed down orally.

In the pre-scientific era the selection of materials was based on data from practical experience. After the works of Pliny the Second ([1469] 1982) and Vitruvius Pollio ([1486] 1992), nothing really important was added to knowledge of limestone down to the treatises of the modern epoch and laboratory experiments in the nineteenth and twentieth centuries. None of the authors mentioned above directly names dolomitic limestone, since classification of rocks is something comparatively recent, but each of them gives more or less cursory descriptions which, if correctly interpreted, furnish precious information.

In general the treatises may contain errors due to the authors being distant from building sites, but Vitruvius' text appears fairly reliable regarding materials and working techniques (Decri 2002). Vitruvius is aware that not all stones with which lime can be processed are the same and that not all of them give the same quality of lime, in terms of performance and use, when he defines some stones for making lime as *optimæ*; moreover, his explanations as a whole demonstrate that he realises that the quality of the binder is also influenced by the techniques used for baking, extinguishing and mixing. He distinguishes two types of rocks that are suited to making lime: light-coloured stone, *de albo saxo*, and hard stone, *silice* (Vitruvius Pollio ([1486] 1992, II-V-1). In effect, pure limestone, which is almost white, could be identified with light-coloured stone, while in Latium the word *silice* was used to refer to a tenacious basalt used to pave roads. It is quite evident that lime cannot be made from basalt, but in colour, hardness and fracture morphology this stone resembles dolomite limestone (Decri 2002).

Going further into the subject of lime production, the author indicates that «quella che verrà prodotta dalla (pietra) densa e più dura, sarà utile nelle murature, invece quella che verrà prodotta dalla (pietra) porosa, negli intonaci . . . » (Vitruvius Pollio [1486] 1992, II-V-1). This observation allows us to establish not only a clear relationship between the appearance of the stone for lime and the respective rock, dolomite limestone or calcareous rock, but also the correspondence between the quality of the product derived and the various uses, dolomite limestone being used to make bedding mortars and calcareous rock for lining mortars.

The theme of the careful choice of the raw material is also present in the work of Andrea Palladio, according to whom, in order to get good lime, the stones, whether from a quarry or a river, must be chosen with care and attention: «ogni pietra de' monti è buona, che sia secca, di humori purgata, e frale, e che non habbia in se altra materia, che consumata dal fuoco, lasci la pietra minore: onde sarà miglior quella, che sarà fatta di pietra durissima, soda, e bianca, e che cotta rimarrà il terzo più leggiera della sua pietra. Sono ancho certe sorti di pietre spugnose, la calce delle quali sarà molto buona all'intonacature de' muri. . . . Ogni pietra cavata à far la calce è migliore della raccolta, e di ombrosa, & humida cava più tosto che di secca, e di bianca meglio si adopra, che di bruna. Le pietre che si pigliano dai fiumi, e torrenti, cioè i ciottoli, ò cuocoli; fanno calce bonissima, che fa molto bianco, e polito lavoro: onde per lo più si usa nelle intonacature de' muri» (Palladio [1570] 1994[2], 8).

One of the first writers in whom we find a more modern scientific attitude is Francesco Milizia, who in 1781 wrote: « . . . tutte le pietre su le quali l'acqua forte[4] agisce e produce effervescenza, sono proprie a far calce: le più dure e le più pesanti sono le migliori . . . » (Milizia [1781] 1847[2]). Hence Milizia too indicates as the best one hard and heavy stone, which, from the cursory descriptions, sounds very much like dolomite limestone. Indeed, evaluating the degree of hardness in accordance with the Mohs[5] scale, and the specific weight of calcite and dolomite, one notices that calcite has a hardness of 3 and a specific weight between 2.65 and 2.80 g/cm^3 while dolomite has a hardness of 3.5–4 and a higher specific weight, between 2.85 and 2.95 g/cm^3. Hence the adjectives «dense», «hard» and «heavy» are well suited to dolomitic rock.

The first publications of a scientific-technical character on the theme being discussed here date from the start of the nineteenth century, when the scientific and systematic study of building materials was asserted. The contributions from this period are particularly interesting because the authors are still aware of the data of traditional experience, daily verifiable in the know-how of manufacturers and mason.

Laboratory experiments began with Vicat (1818), *inspector-general des Ponts et Chaussées* in France, who mostly dealt with hydraulic limes, whose main constituents he identified: calcium, silica, aluminium and magnesium.[6] The author mentions a substantial difference between magnesic lime and dolomitic lime and, during an experimental discussion of the calcination of the raw material on the basis of the baking times and temperature, indicates that a calcareous rock containing 20–25% magnesium carbonate, 10–14% clay and 65–66% calcium carbonate gives rise to excellent hydraulic lime known as magnesic lime; he also emphasises that the latter is not to be confused with dolomitic lime, deriving from the baking of dolomitic limestone which, containing neither silica not aluminium, has no hydraulic properties.[7]

Vicat also mentions an interesting observation made by the Piedmont engineer M. Signorile, according to whom the nature of the fuel has a particular influence on the characteristics of artificial limes deriving from the baking of a mixture of clay and dolomitic limestone. If wood is used as the fuel for calcinations, top-quality hydraulic lime is obtained, while if the fuel is coal, which contains sulphides, the result is lime that sets in a couple of days but crumbles altogether by the fifth. The explanation of this behaviour, according to Signorile, is that in the second case magnesium sulphate and calcium sulphate (chalk) are formed, depriving the mortar of resistance in time. Such a negative outcome seems to be due precisely to the presence of magnesium. Indeed, baking of a clayey calcareous rock without magnesium, with coal, which is saturated with calcium sulphate, gives a product which exhibits no swelling.[8]

Greater sensitivity of dolomitic limes to impurities in the air containing sulphur oxides is also noted by the scholars Leo Wilhelm Berens and Eberhart Schiele, who highlight the fact that mortars containing hydroxide deriving from dolomitic lime are particularly affected by degradation processes, with evident sandiness or pulverisation phenomena (Berens e Schiele 1976, 437).

It was precisely observations like these that prompted specific research aiming at determining the possible differences, in terms of performance and resistance, between mortars made with dolomitic binders resulting from baking with wood-based fuel and those made with binders resulting from baking with coal-based fuel.

While Vicat maintained that 6–12% magnesium enhances the quality of the hydraulic binder,[9] making it indestructible, Winkler (1856), again dealing with hydraulic binders, even considered magnesium oxide a detrimental component since, like calcium silicate, it remains unchanged in water. From that moment on, contradictory theses followed one another down to the start of the twentieth century, when Gallo (1908) published the results of an in-depth study carried out in the laboratory of chemistry applied to building materials at the Royal School of Engineers: he declared that magnesium was dangerous in lime-based mortars. According to the scholar, «la presenza della magnesia nella calce . . . riesce in particolar modo dannosa perché si spegne molto lentamente, e riduce molto la quantità di grassello che una buona calce grassa può dare collo spegnimento; è per questo che si prescrive ordinariamente che una calce grassa, per essere impiegata con profitto, non debba contenere più del 5% di magnesia» (Gallo 1908, 146). The intrinsic incapacity of magnesium carbonate to aggregate in compact structures during evaporation of the mix water is the main reason for the exclusion of magnesic and dolomitic limes from good-quality binders. Indeed, Gallo indicates as fundamental, due to the consequences that can be deduced from it in relation to its use in building, «la grande differenza di solubilità propria dell'ossido di calcio e dell'ossido di magnesio . . . Mentre la calce è solubile in proporzione di gr 1,27 per litro d'acqua a 16° circa, la magnesia invece non è solubile che in rapporto di 1 per 50 mila litri di acqua». And he adds that «la piccolissima solubilità della magnesia, fa sì che sia minima la quantità di essa che può disciogliersi nella massa d'acqua presente, e d'altra parte è lontanissimo l'assorbimento dell'anidride carbonica, da parte della soluzione stessa. Quindi una calce magra per magnesia, fa presa più lentamente, e si disgrega

più facilmente perché non avviene una rapida trasformazione di questa in carbonato, e le varie parti restano disgregate per la interposizione di particelle inattive di magnesia; ne deriva inoltre che il solvente si evapora molto prima che la magnesia si sia trasformata in carbonato, e la massa resta friabile ed incoerente . . . » (Gallo 1908, 149; 154–155).

Although by that time many were against the use of dolomitic limes, in the work of enlarging Genoa harbour in the early years of the twentieth century, after a big debate and numerous experimental trials, concrete[10] was used which was made up of a mortar based on dolomitic limestone from Sestri Ponente[11] and pozzolana. Observation of the varying compression and tensile strength of mortars prepared in different periods of the year led to some experimentation taking various factors into account, including the period when the mortar was mixed, the dampness of the pozzolana and the magnesium content in the limestone. In this connection in 1932 Salvatore Levi noted that «l'elevata percentuale di ossido di magnesio non favorisce certo la resistenza dei calcestruzzi. (tuttavia) massi posti in opera nel 1882 per la costruzione del ponte A. Doria e recentemente salpati non presentano tracce di corrosione pur essendo stati confezionati con tali calci» (Levi 1932, 7).

Actually, we know of no in-depth studies on the subject, and even the regulations for the acceptance of limes,[12] published in 1940, only give vague indications: alongside the subdivision between rich lime in lumps,[13] poor lime in lumps[14] and hydrated lime in powder,[15] the possible use of air-setting magnesic limes containing more than 20% of magnesium oxide is also contemplated.

There are a lot of manuals that give the classification of binders and in these, magnesic limes are mainly defined as rich limes: in 1912 Licurgo Bertelli maintains that « . . . un tenore di magnesia del 10% è già sufficiente per dare ad un calcare il carattere della magrezza, e quando la magnesia raggiunge il 25 o il 30% non può più essere impiegato . . . Le calci magre contengono magnesia e questa . . . è la causa della loro deficienza di rendimento; inoltre l'ossido di magnesio si idrata molto più lentamente e, per la sua debole funzione basica, compie più difficilmente le reazioni che producono l'indurimento delle calci grasse. Queste calci vengono generalmente rifiutate dai costruttori» (Bertelli 1912, 82 and 93) and in 1922 Luigi Mazzocchi indicates as « . . . "calci magre" quelle provenienti dalla cottura di calcari magnesiaci (dolomie). Esse possono contenere sino al 50% di magnesia, ma basta anche il 10% di magnesia per rendere «magra» una calce . . . il loro rendimento[16] in grassello è tanto minore quanto più è elevata la percentuale di magnesia» (Mazzocchi 1932^6, 11).

It is only in more recent times that different opinions have been expressed. For example, according to Bolis, « . . . le calci con più del 20% di magnesia (MgO) prendono il nome di «magnesiache»; una piccola percentuale di magnesia smagrisce la calce, una del 40–50% fornisce invece un'ottima calce paragonabile alla grassa . . . » (Bolis 1961) and, like him, Piepoli maintains that « . . . le calci grasse, ottenibili da calcari con non oltre il 10% di impurità (fra silice, magnesia, allumina), oppure anche da dolomie con quantità pressocché equimolecolari di calce e magnesia, si spengono rapidamente e con forte sviluppo di calore, dando un grassello bianco, omogeneo, dolcissimo al tatto e all'incirca il triplo, sia in peso che in volume, della calce viva adoperata . . . » (Piepoli 1980).

TECHNOLOGY AND SCIENCE

It is curious to notice that in quite a short period of time, just over fifty years, scientific thought regarding the presence of magnesium in lime changed radically. So it seems natural to wonder what changed from the second half of the nineteenth century to the first half of the twentieth. The historical-archaeological analysis that has been going ahead for years in the Ligurian territory and more in general in the regions of Northern Italy shows that the change in the quality of products went hand-in-hand with one of the most important revolutions in the building field: the introduction of the cementitious binder and the revolution in production technologies. There was a transition from intermittent kilns[17] of a pre-industrial type, with bundles of wood sticks as the fuel, to continuous kilns of an industrial type, burning first coal and then mineral oils and natural gases. The influence of the type of fuel used on the oxide product of dolomitic limestone decomposition is already reported on, alongside other indications, by various authors, though without ever being analysed from the scientific point of view. Deville, in a study on

cement made with magnesium oxide, obtained by means of calcinations of magnesium chloride, mixed with calcium carbonate, reports that «Per poter preparare il cemento Deville in proporzione industriale, si cercò di utilizzare la dolomite che, riscaldata a temperatura inferiore al rosso perde l'acido carbonico che è combinato alla magnesia e non quello combinato alla calce» (Ghersi 1903). Vicat too indicates that hydraulic limes are baked with wood fuels to set in soft water, because the heat produced is adequate, moderated in such a way as to arrive at shaded red and subsequently at red heat for enough time to expel all the carbonic acid.[18] Bertelli, quoting a study by Maede (1909), maintains that it is possible to eliminate the drawbacks connected with the use of calcareous stones with too high a magnesium content for making Portland cement, indicating that the disgregation phenomenon « . . . è dovuto essenzialmente alla cottura alla quale è stato sottoposto il cemento. Conferma questa opinione il fatto che nei cementi cotti a temperatura bassa la magnesia non è nociva: tali i cementi romani; e ancora il fatto che proporzioni anche notevoli di magnesia, ottenuta per decomposizione del carbonato a temperatura normale, aggiunta ad un cemento, non ne modificano le proprietà» (Bertelli 1912, 498).

Once again there seems to be a link between the performance of the final product and the baking mode, though the explanations offered are vague and mostly based on empirical observations. These indications, linking the properties of dolomitic mortars to the temperature at which they are baked, in point of fact also indicate a dependence on the type of fuel used: wood or coal.

Hence it was considered interesting to analyse[20] the influence of both the temperature and the type of fuel on the decomposition product, starting from the study of gaseous atmospheres.

The study of the atmospheres present in kilns fired with different fuels has made it possible to identify significant differences between the contributions of the different components of the fumes.

	CO_2 [Nm^3/kg]	H_2O [Nm^3/kg]	SO_2 [Nm^3/kg]	N_2 [Nm^3/kg]	Total V_{FT} [Nm^3/kg]
Wood[21]	0.926	0.675	—	0.001	5.378
Coal	1.122	0.542	0.006	0.007	6.259

The composition of the theoretical fumes clearly shows the difference between the quantities of carbon dioxide and steam: during combustion, wood fuel produces less carbon dioxide but more steam than coal.

However, the most significant datum emerges from the calculation of the partial pressures, linked to the total quantity of theoretical fumes,[22] which shows that the partial pressure of the steam, in the wood-fired kiln, is about twice as high as that present in the kiln fired with coal.

	P_{CO2} [mm Hg]	P_{H2O} [mm Hg]	P_{SO2} [mm Hg]	P_{N2} [mm Hg]
Wood	130.805	95.381	–	0.113
Coal	136.183	65.752	0.696	0.836

Neglecting the partial pressures of carbon dioxide and nitrogen, which are decidedly low and hence have no influence on the dolomite limestone mass, an analysis was made of the effect of the carbon dioxide and the steam on the microstructure of the grains of calcium oxide and magnesium oxide produced during dolomite decomposition.

In the scientific literature, the effect of carbon dioxide on the microstructure of calcium oxide, produced by the decomposition of the calcium carbonate, was already well known. At low partial carbon dioxide pressure the oxide still has recollection of the initial crystalline form, while high carbon dioxide pressures favour sintering of the grains, so that bigger grains with a different shape are formed. The same effect has been observed between steam and magnesium oxide: the steam catalyses the decomposition of the magnesium carbonate, above all at low temperatures, rendering the oxide product unstable and provoking localised collapses in the microstructure. The sintering of magnesium oxide inside grains that maintain their global volume increases the total porosity of the sample and the average size of the pores.

Hence in an atmosphere of carbon dioxide alone, the zones of the oxide product prove to be made up of big grains of calcium oxide and small grains of magnesium oxide, not sintered. In an atmosphere of carbon dioxide and steam, both the calcium oxide and

the magnesium oxide zones are made up of big grains, with consequent higher porosity.

Decompositions carried out in wood-fired kilns and hence in an atmosphere rich in steam produce magnesium oxide with a large grain and pores that are more accessible to reagents. Towards liquid phases this microstructure should have greater reactivity[23] that, in the case of extinction, is translated into better hydration because of the formation of lime paste.

Only now does it appear possible to understand indications like the one given by Misuraca (1900, 179), namely that « . . . Sembra che una corrente di vapore acqueo, durante il periodo di demolizione per calcinazione del calcare, agevoli la decomposizione medesima. Era ritenuta perciò buona norma quella di mettere un recipiente con acqua sulla soglia della bocca da fuoco, durante l'operazione di cottura, perché il vapore acqueo potesse facilmente essere trasportato nella massa incandescente . . . »

NOTES

1. Utilised in Egypt, perhaps even before the Ptolemaic period, it was known to the Minoans, the Myceneans and the Greeks in the archaic epoch, who used it above all in linings, but it was also used in a systematic and widespread way in the Roman epoch, towards the end of the 3rd century BC (Davey 1965, p . . . .)
2. «Il cemento è in realtà un legante in grado di produrre malte e calcestruzzi a bassissima porosità, molto rigidi e ad alta resistenza alla compressione, con un'elevata dilatazione termica, vicina a quella del ferro, ma con una conducibilità assai più bassa. Queste caratteristiche fanno sì che con il cemento armato si possano costruire strutture foggiabili a volontà, e in grado di sostituire qualsiasi altro materiale portante, anche in presenza di acqua. In ambiente atmosferico, tuttavia, il cemento può dare luogo nel tempo a degradi fisici e chimici legati proprio alle sue caratteristiche intrinseche (per esempio: lesioni di spigolo per sbalzi termici, creazione di solfati dannosi).
   Per un certo tempo si è creduto, inoltre, che l'impermeabilità del cemento ne facesse un ottimo materiale per i rivestimenti esterni: oggi si è capito che sono più igienici i muri idrorepellenti all'esterno, ma in grado di permettere una traspirazione dell'umidità dall'interno verso l'esterno». (Mannoni 2000, 7).
3. Dolomite limestone is a rock of sedimentary origin containing a large quantity of the mineral dolomite. Ideal dolomite is made up of a crystalline reticule of alternate strata of calcium ions and magnesium ions, separated by strata of CO_3 and is typically represented by a stoichiometric chemical composition of $CaMg(CO_3)_2$ in which calcium and magnesium are present in equal proportions.
4. I.e. hydrochloric acid (HCl).
5. A scale of hardness, defined as resistance to scratching, made up of ten mineral substances empirically ordered by mineralogists in such a way that each one incises the one immediately below and is incised by the one immediately above. Resistance to scratching is measured, for comparison purposes, by the incision produced by one of the minerals belonging to the Mohs scale (Talc 1, Chalk 2, Calcite 3, Fluorite 4, Apatite 5, Orthoclase 6, Quartz 7, Topaz 8, Corundum 9, Diamond 10). (AIMAT (ed.) 1996, 138–139).
6. «La chaux, la silice, l'alumine et la magnésie, sont les principes essentiels dont se component les gangues qui lient les matériaux employés dans les constructions» (Vicat 1856, 1).
7. «On rencontre quelquefois des substances calcaires tenant, indépendamment d'une certaine quantité d'argile, du carbonate de magnésie; quand ces calcaires, pour 20 à 25 parties de ce carbonate, referment d'ailleurs de 10 à 14 parties d'argile et de 65 à 66 de carbonate de chaux, on peut en tirer pa la cuisson d'excellentes chaux hydrauliques qui prennent alors le nom de chaux magnésiennes, et qu'il ne faudrait pas confondre avec les chaux dolomitiques, provenant des dolomies proprement dites, lesquelles ne contiennent ni silice ni alumine, et conséquemment ne sont pas hydrauliques» (Vicat 1856, 11–12).
   This is well demonstrated in the good 2. Piedmont limes, obtained from slightly clayey dolomite limestones.
8. «Un ingénieur piémontais d'un grand mérite, M. Signorile, dans un très intéressant Mémoire, a signalé l'influence particulière exercée par la nature du combustible sur les qualités de certaines chaux artificielles résultant de la cuisson d'un mélange, en bonnes proportions, d'argile et de chaux tirée de dolomies; il a reconnu que ce mélange, cuit à la houille contenant des sulfures, cette chaux, après avoir fait sa première prise en deux jours, tombait en boue le cinquième.
   L'analyse comparée des deux produits signalait dans le dernier une notable quantité de sulfate de chaux n'existant pas dans le premier ; d'un autre côté, un calcaire argileux, exempt de magnésie, cuit aussi avec la même houille, et chargé aussi en sulfate de chaux, ne présentait dans les mêmes circonstances aucun symptôme de boursouflement. Nous bornons à rapporter ces faits singuliers, dont la responsabilité reste à l'habile observateur de qui nous les tenons» (Vicat 1856, 14).

9. «On rencontre quelquefois des calcaires dont l'argile contient, outre la silice et l'alumine, une quantité de magnésie de 6 à 12 pour 100 ; la présence de cette base paraît exalter la qualité du ciment pour les travaux à la mer» (Vicat 1856, 42).
10. In the proportions, in volume, of 1:2 with calcareous gravel in the proportion of 1 of mortar and 2 of gravel, for slightly over 1 m^3 of concrete (Levi 1932).
11. Levi reports the results of an analysis of Sestri Ponente lime that he followed: «SiO_2 2,74 – Al_2O_3 2,04 – Fe_2O_3 0,92 – CaO 56,76 – MgO 35,30 (. . .).» (Levi 1932, 7).
12. Norme per l'accettazione delle calci, Royal decree of 16 November 1939, 2331, Milan 1940, 12–31.
13. « . . . di colore pressocché bianco, è il prodotto della cottura di calcari [con un] contenuto in CaO + MgO = 94% in peso [. . .] deve avere un rendimento in grassello = 2,5 m^3/t» Norme per l'accettazione delle calci, Royal decree of 16 November 1939, 2231, Milan 1940, 13.
14. « . . . è il prodotto della cottura di calcari [con un] contenuto in CaO + MgO = 94% in peso [. . .] deve avere un rendimento in grassello = 1,5 mc/t» Norme per l'accettazione delle calci, Royal decree of 16 November 1939, 2231, Milan 1940, 13.
15. «. . . è il prodotto dello spegnimento completo delle calci predette, fatto dallo stabilimento produttore in modo da ottenerla in polvere fina e secca. [. . .] Questa calce comprende due categorie di prodotti, per i quali devono essere soddisfatti i seguenti requisiti: fiore di calce: contenuto in umidità = 3%; contenuto in carboni e impurità = 6%; contenuto in idrati di calcio e magnesio = 91%; deve dare un residuo al vaglio da 900 maglie/cmq = 1%; deve dare un residuo al vaglio da 4900 maglie/cmq = 5%; deve rispondere alla prova di stabilità di volume; calce idrata da costruzione: contenuto in umidità = 3%; contenuto in carboni e impurità = 6%; contenuto in idrati di calcio e magnesio = 82%; deve dare un residuo al vaglio da 900 maglie/cmq = 2%; deve dare un residuo al vaglio da 4900 maglie/cmq = 15%; deve rispondere alla prova di stabilità di volume»
16. «Il rendimento di una calce [è] il volume assunto dalla pasta per rispetto all'originario volume di calce viva sottoposto allo spegnimento. È questo straordinario rendimento, [per la calce dolce o grassa]da 3 sino a 3 volte e mezzo il volume primitivo, il vero motivo per cui in talune fabbriche la calce dolce è tuttora dai costruttori preferita alle calci idrauliche» (Mazzocchi 1932[6], 8).
17. Kilns are defined as intermittent when they require distinct and successive phases to work: loading, baking, cooling and unloading (AA VV 1839, 512; AA VV 1878, 61–62). The typical layout of an intermittent production unit, fired with wood, is made up of a *vase* with a circular plan that develops vertically to create a cylindrical structure, ending in a pseudo-vault and surmounted by a chimney. Inside you can always see a wrapping ring going even two-thirds of the way up and marking the impost of the apertures above. This structure has the task of facilitating loading operations, in that the upper level can easily be reached. The inside diameter of kilns, measured at the height of the wrapping ring, varies from a minimum of four to a maximum of six metres; the inside height, measured in line with the central chimney, varies independently of the width, and oscillates between eight and twelve metres. The main entrance is the only aperture at the base of the kiln and is often done with a double splayed stone or brick arch. There are generally three upper apertures, placed at the vertices of an imaginary isosceles triangle inscribed in the base circumference. Above, other minor apertures and air vents vary in number, shape and position in the curvature of the pseudo-vault, in different kilns. A characteristic element of every lime kiln is the chimney at the top of the pseudo-vault, whose shape is always different.
18. «On remarque qu'à composition égale, les chaux hydrauliques sont, pour l'emploi en eau douce, meilleures cuites au bois qu'au charbon; cela peut tenir, principalement, au degré d'intensité de la chaleur produite; la meilleure chaux, pour l'emploi spécifié, serait celle pour laquelle une chaleur modérée, correspondant au rouge qui succède au rouge sombre, aurait été soutenue assez longtemps pour en expulser tout l'acide carbonique; cette observation serait en défaut pour l'eau de mer» (Vicat 1856, 8).
19. This denomination comprises all hydraulic products from clayey calcareous stones with a high clay content, baked at a moderate temperature, below the fusion limit, and pulverised by grinding with mechanical means. The product of the grinding is yellowish with red-brown nuances. Such cements set rapidly, in 5–10 minutes, with very elevated hardening. (Bertelli 1912, 352–358).
20. In the framework of the Postgraduate Course in Materials Engineering, 15th cycle of the Milan Polytechnic, held by the present writer at the Department of Building, Urbanistic Studies and Materials Engineering of Genoa University.
21. As regards the composition of the wood, an average was calculated between the trees that we know from historical sources to have been used (beech, pine, alder, juniper and sessile oak).
22. The quantity of theoretical fumes produced by wood (5,378 Nm^3/kg) is lower than that produced by coal (6,259 Nm^3/kg).
23. The next stage of the research, at present being organised, consists precisely in evaluating the reactivity of the oxide product in the presence of steam.

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Brick covered steel framework constructions Palazzo della Rinascente by Giulio de Angelis, Rome, Italy (1886–1887)

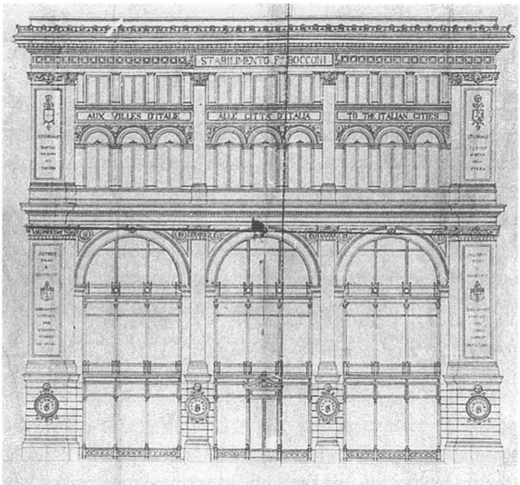
Paolo Verducci

«The true significance of the "turning-point" of the 19th century», states Edoardo Benvenuto, «lies in the shift of attention from the geometrical form of the construction to the mechanical properties of its materials. There are two predominant aspects in this shift of interest from the engineers and scientists of the polytechnic schools in the early 19th century, compared to the old *science des ingénieurs*: the first is the concentration of attention on the mechanical properties of materials and their fulfilling of needs; the second aspect lies in a new interpretation of buildings from which we can perceive the traces of more or less elementary structures.[1] Within this «shift of interest», the separation of the external covering from the internal structure of the building became the preferred area of research in the study of «heavy and light» which lasted for most of the 2oth century, up until the arrival of contemporary *High-Tech* constructions. Therefore the study of 19th century buildings in which the function of the external brickwork was to pad, insulate and protect against fire whilst iron was used as a purely structural element, takes us back to the origins of construction techniques, ignoring their aesthetic or formal implications. It also helps us to understand the reasons which led the Modern Movement to take the liberation of the bearing structure from its external covering[2] as its main field of research between architecture and new technologies.[3]

To better understand the aspiration to this continuous external covering, extensive and self-supporting, a screen free from any direct implication with the structural frame, one uses the term «curtain-wall» taken from the renowned manual, *Cyclopedia of Architecture, Carpentry and Building* (Chicago, 1907).

Curtain walls, or rather those erected between iron or steel uprights and which bear no weight but their own, are only as thick as is necessary to protect the outside of the building and sustain the upper walls. In the case of skeleton constructions or those in which all the walls like other parts of the building are supported by steel or iron uprights, the walls need only be thick enough to protect the building and its structure from atmospheric elements unless they are

Figure 1
«La Rinascente» in an old photograph



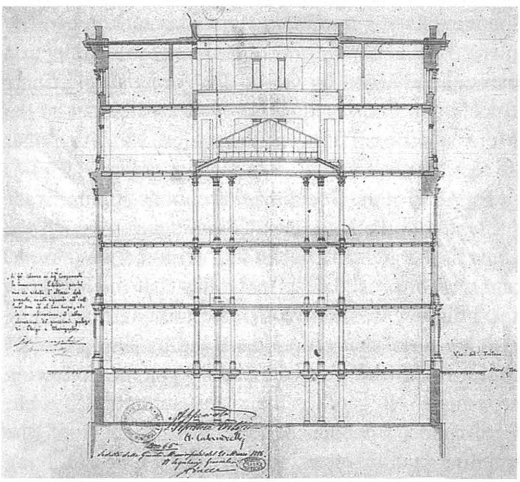


Figure 5/6
Section and elevation. Original version

the demolition of a building found close to Palazzo Chigi, it cost the then exorbitant sum of Lire 900,000. However, according to Renato Lefevre, «The Bocconi brothers knew what they were doing and paid little attention to the cost of laying out such an imposing structure, neither did they allow themselves to be influenced by historic or environmental constraints. They brought their work to life based upon a style and technique that were then considered avant-guard: the internal structure had a completely innovative air thanks to the use of the large Renaissance style round arched loggias which gave the immediate impression of visible communication between the internal and the external and an absolute prevalence of emptiness over heaviness».[11]

The economic reasons mentioned above along with the dimensions of the plot, which was actually a trapezium measuring 30.2 m by 28.3 m by 30.3 m by 27.9 m, heavily contributed to the typological solution of the building: in a relatively compact space they had to create an area dedicated to sales and another dedicated to production.

Speaking of Palazzo della Rinascente, Romano Jodice claims that «its typological and spatial characteristics can also be found in its contemporaries such as the Parisian department stores of the 1870s and 80s , particularly in Boileau, Moisant and (possibly) Eiffel's Bon Marchè (1873–76, Rue de Sèvres) and more so in Printemps by Paul Sèdille who began work in 1881 in Boulevard Hausmann and finished in 1885 but by 1883 had already completed a good part of its construction. It is from Printemps that Palazzo della Rinascente took inspiration for its metallic wall decorations which have now all but disappeared».[12]

Almost in contradiction to the distinct separation (which is very evident from outside the building) created between the sales area (public) and the production area (private), De Angelis then introduced a highly unifying element to his work: a large, open, central space measuring 9.45 m by 8.85 m, covered by a skylight around which he arranged a perfectly symmetrical array of cast iron columns. Despite being incoherent with the style of the time, this arrangement allowed for people to see and indeed be seen from each floor, it also allowed light from above to be evenly dispersed to each level. In contrast it is perfectly adapted to the current use of the building.

This great central opening, without doubt the most interesting idea even from a commercial point of view, was characterised by the varying decorative motifs on the cast iron pillars.

Portoghesi states that, «the designs on the pillars vary according to each floor and follow a pattern of simplistic decoration on the lower floors, growing increasingly more complex towards the higher floors. Systematic alterations to these decorative elements and the radical transformation of the ground floor have profoundly altered the original aspect of the

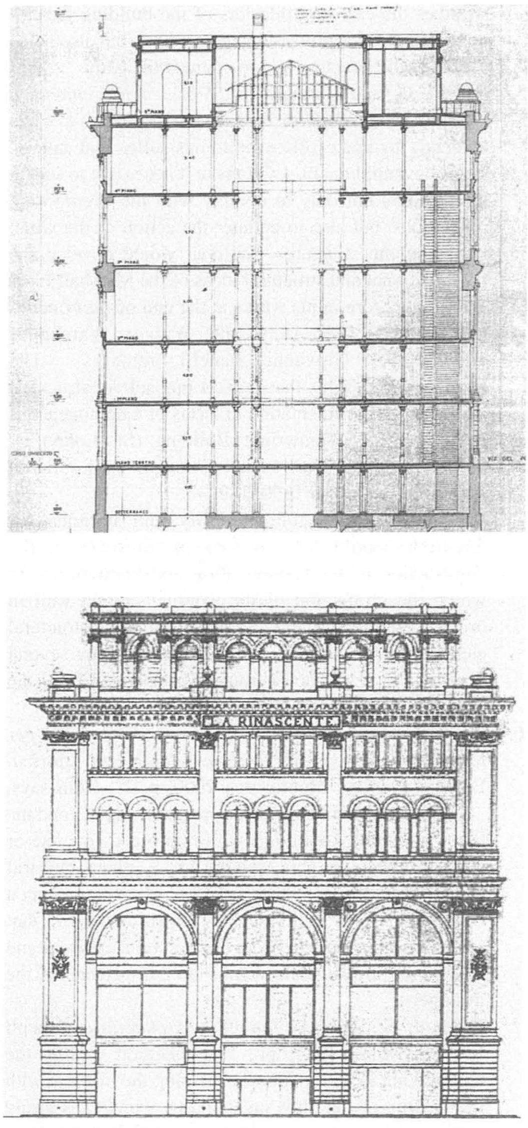


Figure 7/8
Section and elevation of the central space before the 1974 restoration

warehouse, but we can still see the simplicity and legibility of the static organism and the graduation of the influx of light which remains unaltered on each floor thanks to the size of the openings which decrease the higher up the levels you go».[13]

The opening of the «industrial palace» at the end of the century in Umbertine Rome, was a clamorous event. The fierce regulatory debate, the construction and labour crises, Crispi's political war and indeed that against him, even the mournful war in Africa, all this was momentarily swept aside. The importance of this great event was ratified by the presence of King Umberto himself. Referring to the various articles which appeared in the press of that time, Renato Lefevre16 reported; «Come down from his Victoria and accompanied by his field assistant Cavalier Caccianino, the sovereign was received by brothers Ferdinando and Luigi Bocconi, governor Oddo Giambartolomei, the architect authors of the project, and by governors from Milan, Palermo, Genoa, Turin and Naples who had gathered in Rome for the occasion. It was a scrupulously planned visit, lasting about an hour and not without a number of questions regarding the commercial characteristics of the firm, its technical innovations, its administrative organisation and even the welfare measures it took for its numerous employees. «I wish upon this well-deserving house all the good fortune and business of its inspiring force, Paris' Bon Marchè», declared Umberto I to the applause of the crowd».

Later, changing technical-productive conditions, increasing sales and the need for more office space meant that the building had to be exploited to the full. Eventually more storeys were added and in more recent times its renovation saw the addition of elevators and modern lifts.

To conclude, despite the inspiration it took from the aforementioned French models and indeed other European examples, the Palazzo della Rinascente is nontheless without doubt a highly advanced piece of work compared to its Italian counterparts, both on an architectural and technological level.

The relationship between its outer covering and its internal structure of cast iron pillars is testimony to the research that went into the rapport between light and heavy, something that, as stated at the beginning of this essay, covered a large part of the Modern Movement up to its fading contemporaries.

NOTES

1. Benvenuto, E., *La Scienza delle Costruzioni ed il suo sviluppo storico*, Sansoni Editore, Florence 1981. «New

"characters"», states Benvenuto, «truly become the protagonists: in particular, *tension* and *deformation*, to which *safety limits* must be set. The considerably longer season of the previous science of building was instead marked by other *preeminent* problems: for example that of guaranteeing a composition of elements —such as the stones of a masonry structure, of an arch or of a dome— that would prevent the onset of kinematic motion. Because of this, in the past the *geometric form* of the building was the protagonist of the structure; the compositional inventiveness and the static compatibility were two inseparable constituents of a single design process. Now instead the use of metallic materials, made available in great quantity, allows a certain "liberation" of formal variables, dominating unusual static designs».

2. According to Semper, originally the architectural shell consisted of hanging fabric. With the advent of masonry structures the image of a shell composed solely of fabric was lost, and was translated into the outer covering. The glass shell, with the wall eliminated, stands conceptually as the solution of the origins». Semper writes in *Der Stil*, «in all of the Germanic languages the word wall (Wand), which has the same root and the same substantial meaning as dress (Gewand), recalls the ancient origin and the typology of the enclosing of space». (Semper G., *Der Stil in den technischen und tektonischen Künsten oder praktische Ästhetik. Ein Handbuck für Techniker, Künstler und Kunstfreunde*, vol. I, Frankfurt am Main 1860, vol. II, Munich 1863.
3. Verducci, P., *Il progetto dell'immateriale, il percorso della trasparenza nella storia, nei materiali e nelle tecnologie,* edizione Galeno-Margiacchi, Perugia 1997, p. 9. The history of the Modern Movement, for example, can be seen also as the history of the progressive «emptying» and «breaking down» of the brick or stone box in which the abstraction process of architectural elements has made possible a type of architecture that we can call «immaterial», composed only of surfaces, lines, planes: «in short, we can say that the Modern Movement created the possibility of an architecture made of pure geometric signs». The process of breaking down and dematerializing the brick or stone box as an attempt at attaining a lighter and more transparent architecture has also brought about the dividing of the building into two distinct parts: the internal organism and the external shell.
4. American Technical Society, edited by, *Cyclopedia of Architecture, Carpentry, and Building*, Chicago 1907 (1916), vol. V, pp. 149, 150.
   The first example of a metallic frame covered in masonry and extending also to the façade is found in the Home Insurance Building (Chicago 1884) by William Le Baron Jenney, demolished unfortunately in 1931. In the Home Insurance Building the brickwork that sheathes the cast-iron pilasters of the building façades not only provides protection against fires, but also helps to stiffen the structure and to connect the parts.
5. Fanelli, G. and Gargiani, R., *Storia dell'architettura contemporanea*, Editori laterza, Bari 1998, p. 4. «The tendency to make office buildings taller and taller», says Giovanni Fanelli, «will make it necessary to sheath the pilasters not only to comply with the fireproofing regulations, but also to counter the action of the wind, stiffening the structure». Sullivan would develop the compositional and structural ideas of the Marshall Field Wholesale Store in his works at the end of the Nineties (Auditorium 1886–1889 and Walker Warehouse 1888–1889). Giovanni Fanelli remarks, «The architectural designs that mark a pinnacle in structural and formal experimentation in terms of a homogeneous frame are the Wainwright Building (St. Louis) by Sullivan and the Fair Store (Chicago) by Le Baron Jenney, both built in 1890–1892».
   The pursuit of tectonic solidity and lightness of materials would be achieved by Sullivan in the construction of the Carson, Pirie and Scott stores, in which the rarefaction of the external curtain wall in order to obtain a progressive reduction in the structural elements of the façades would foreshadow by several decades the glass shell completely separated from the load-bearing structure of the building.
6. Gulli, R., *Métis e techne, Gli strumenti del progetto per la manutenzione e il recupero della città storica*, Edicom edizioni, Monfalcone 2000, p. 28. Gulli says, «A differentiation that extends progressively beyond the space marked by buildings with reinforced concrete or steel frames; in this separation a clear cultural dichotomy has taken shape which has lead to making a distinction, even with masonry construction, of that which pertains exclusively to the structural engineer and that which instead falls within the competence of the designer».
7. Giedion, S., *Spazio, Tempo e Architettura*, Hoepli Editore, Milan 1984, pp. 182. Giedion praises the undertaking in heroic tones, lamenting the fact that with the passing of time this undertaking, which was «truly extraordinary for the builders of the time», has been virtually forgotten. It seems that **I** beams were used for the first time ever in this factory built in Salford, and that the Scottish engineer William Fairbairn praised this as the first example of the intuitive knowledge of the most efficient form, well before it was demonstrated with calculations. The Salford experiment, later observed by Fairbairn in 1854 and cited by Giedion, «was at the vanguard of the method of fireproof construction that now characterizes the industrial areas of this country. For a quarter of a century this spinning mill was a model for similar buildings. From 1801 to

1824 no changes of any consequence were made to the shape of the beams».

8. Gargiani, R., «Henri Labrouste, ornamento e costruzione nella biblioteca Sainte Geneviève a Parigi (1839–1850)», in *Casabella*, no. 645, Elemond editore, p. 62. Gargiani observes, «The proportions of the slender columns no longer follow the canons of the architectural order, of which only the ornamentation remains, but are derived from the calculation of the resistance of a cast-iron pier. The Galilean and Lodolian logic of the constructive truth of materials, which in the early decades of the 1800s was undermining also the Vitruvian myth of the metamorphosis of the tree trunk into a marble column, prevails over the criterion of imitation, producing a new hierarchy of orders depending on the materials: the order of wood, the order of stone, and, with Labrouste, the order of metal».
9. Miano, G., *Figure e voci per la città capitale, «Architettura e Urbanistica-Roma Capitale 1870–1911, uso e trasformazione della città storica»,* Marsilio Editore, pp. 36–39. «De Angelis's works are known», says Giuseppe Miano, «and are found in all of the treatises on architecture in Rome regarding those years. Thus a biographical reconstruction of his life is necessary, even if only in outline. De Angelis was born in Rome in 1850 and died in Anzio on March 14, 1906, although he did not grow up in Rome, having spent most of his youth in Perugia. [. . .] De Angelis always remained closely tied to Perugia and its Academy, such that on March 9, 1876, at the age of just twenty-six, he was named honorary professor. His early training in Perugia was decisive, as was equally the completion of his studies at the Politecnico of Milan, after 1866, the year in which he participated in Garibaldi's military campaign, despite being only sixteen years old. At the Politecnico he had the opportunity to gain considerable knowledge in the field of engineering; in particular, he must have approached the new technologies of iron, which would characterize his mature works». After working on a number of projects in Perugia (the barracks of the *carabinieri* and participation in the renovation of the Morlacchi theater), De Angelis moved permanently to Rome, where he built the house of Ruggero Bonghi, then the Minister of Education. The Bonghi villa in the Macao quarter, defined one of the most interesting of the period, allowed him to obtain a certain renown, such that «besides being visited and receiving praise, as in the case of Mengoni and Boito, it was admired also by the Marquis Selvatico, a true authority on 19th-century art in Italy and the master of Boito». Later De Angelis, by now established in Rome, created one of his most interesting works: the renovation of the Sciarra Gallery and the building of the edifice between Via delle Muratte and Via Minghetti. In this period metallic structural elements and cast-iron columns produced by the Barbieri foundry of Castelmaggiore made their appearance, and would become characteristic of his future designs. In 1886, after winning a competition together with Sante Bucciarelli, he planned his most famous work: the Magazzini Bocconi. In the same period he also designed the head office of the *Popolo Romano* newspaper in Via Due Macelli for Costanzo Chauvet (1844–1918) of Piedmont. In the last part of his career, it seems that he substituted his professional activities with a certain inclination to accept public appointments. >From 1889 to 1895 De Angelis sat in fact as a councilor in the municipal council of Rome. He ended his career (dying at just fifty-six years of age) as the director of the technical office for the preservation of monuments in the city and province of Rome and in the provinces of L'Aquila and Chieti, in the 1899–1902 period, and he supervised the restoration of important Roman monuments, including the Thermae of Caracalla.
10. The file on the Rinascente building can be consulted at the Archivio Capitolino (Capitoline Archives) in Rome (prt. Gen. 17726–Titolo 54–1886). In particular, by consulting the minutes once can sense the unanimous consent of the Building Commission in approving the greater height of the building in regard to the Code in force at the time. Also worthy of note is the speed with which the project was approved. The plan was presented by Mr. Ferdinando Bocconi on February 5, 1886, and the building permit was issued on March 20, 1886 (about a month a half later). In fact, Ferdinando Bocconi himself appealed to the Mayor of Rome, Duke Torlonia, in order to « . . . urgently obtain the relative approval». Later, on February 18, 1886, the plan was presented again in order to obtain slight modifications. Three drawings are enclosed: the plan of the ground floor in 1:100 scale; the front elevation in 1:100 scale, and the section of the interior in 1:100 scale.
11. Lefevre, R., «Roma 1887. Il palazzo industriale dei Fratelli Bocconi», in *Strenna dei Romanisti. Natale di Roma 1975*, Staderini s.p.a., Rome 1975, p. 250. Renato Lefevre observes, «It is particularly interesting to reread, almost ninety years later, the news reports of the time and also the advertisements in December 1887 which announced, in block letters, the opening of the great retail establishment —Saturday evening, December 10, 1887, at 8:30 a.m.. Inauguration— (by invitation) —of the Industrial Building— to the Cities of Italy-Bocconi Brothers —Sunday 11, from 12:00 to 3:00 p.m. and from 6:00 to 9:00 p.m.— Open to public visits-inside the building —Monday 12– sales opening.
12. Jodice, R., *L'architettura del Ferro, l'Italia 1796–1914*, Bulzoni Editore, Rome 1985, p. 508. Jodice comments, «While the Sèdille's Grands Magazins seems to furnish

a plausible source of inspiration as regards its neo-Renaissance loggia design, in its overall architectural physiognomy the Rinascente building possesses an expressive, figurative and spatial dignity of unquestionable value which puts it among the greatest achievements in Italian architecture of the period and amply justifies its current status as a protected building established by the Superintendence of Ancient Monuments and Fine Arts».

13. Portoghesi, P., *L'eclettismo a Roma. 1870–1922*, De Luca, Rome 1967, p. 56. Portoghesi states, «for the architect, the use of cast iron is not a starting point for a new constructive synthesis, but rather an unusual pretext for increased ornateness; it is a brilliant solution to a particular problem, that of the illuminating of the store envisaged, in a concept that was gaining ground, as space in direct contact with the outside, projected toward the street with intentions of both an advertising as well as a city-planning nature». Furthermore, as concerns the relationship between the iron structure and the masonry covering, he says, «There is a juxtaposition of two structures, one light and one ostentatiously massive, which coexist one inside the other, following a plan that could be connected with that of certain medieval windows in which the vibrant lacework of the mullioned openings function as a simple diaphragm within the strong frame of the arch».

Critical study of the Specifications for the construction of the nuns' monastery of Chinchón, a contribution to the knowledge of Spanish constructive system in the construction time of El Escorial

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Many Specifications of architectural works of the period, even from Nicolás de Vergara, the author of this Specifications document, have lasted through time until the present. Marías (1985, 55–100) states that different Specifications were granted more than fifteen times. Specifications, was a fairly common document which was submitted with the drawings and plans of architecture projects in the second half of the 16th century.

A critical analysis of this Specifications is of a high interest value for the study of the history of architecture; an approach that has not much been practiced up to now. The fact that the transcription of the Specifications has already been published (Marías 1980), together with the possibilities of checking the works done «in situ», has motivated us to choose for this study, the Specifications of the nuns' monastery of Chinchón,[1] village which has already been of interest for other studies in the history of architecture (Villanueva 1998).

Historical background

On July 26th, 1597, Diego Fernández de Cabrera y Bobadilla, 3rd Count of Chinchón, and the stoneworkers and masonry masters Juan de las Heras, Pedro de Pedrosa and Juan de Bozarraiz signed the Specifications document for the construction of a nuns' monastery which the Count wanted to found in Chinchón.

Fernando Marías (1980) has published the transcription of such Specifications entitleling it as «Condiciones como se a de haçer la obra del monasterio de monjas en la villa de Chinchon por mandato de sus señoría el Conde de Chinchon conforme a unas traças plantas y monteas firmadas por su señoría que son de Niculas de Vergara»[2] (Condiciones 1597, 1).

The process had been initiated years before, since there are news as early as from the beginning of the16th century of the founding wishes of the 1st Count, Fernando de Cabrera and grandfather of Diego. Nevertheless, his desires did not come true until the end of that century (Marías 1980, 258).

On October 22th, 1596 a first contract was signed between Count Diego and Juan de Bozarraiz or Bozarraez, mason master (Protocolos 1596 a; Condiciones 1597, 12). Shortly after that, Bozarraiz handed the work over to Heras and Pedrosa, stoneworker and masonry masters, so that after signing a new contract with Count Diego, they would work as a company (Protocolos 1596 b). This new contract was delayed until the 29th of July 1597 (Protocolos 1597), that is, three days after the signature of the Specifications (Condiciones 1597, 45).

Diego, 3rd Count of Chinchón since 1575, who died in 1607, was a close friend of Philip the 2nd and member of the Council for Business and Difficult Matters. He advised the king on architectural matters, and therefore he had been his councilor in the works of El Escorial (Villanueva 1998).

Nicolás de Vergara, Jr., named so, to distinguish him from his father Nicolás de Vergara, Sr.,[3] was the master builder of the cathedral of Toledo, between 1575 and 1582 and later, from 1587 up to his death in 1606. He was also the master builder of the town council of this city since 1576. He occupies the most relevant position in the architecture of Toledo in the last quarter of the 16th century, linking together Covarrubias with Monegro. (Villanueva 1970; Marías 1983). He follows the tendency of Juan de Herrera, from the moment he visited him in El Escorial to consult him about the plans of the church of Santo Domingo el Antiguo, church which would become the model of the Manneristic period. As the master builder of the cathedral in Toledo, he designed numerous churches in the archdiocese. His major works are the Sacristy of Tavera, Saint Peter Martyr and the Shrine in the Cathedral of Toledo. According to Marías: «he stands out among his contemporaries due to his quality as great innovator, starting off from Juan de Herrera but achieving unexpected accomplishments of great originality» (Marías 1986).

In 1593, Nicolás de Vergara visited Chinchón, to inspect the works done of the parish church, built under the patronage of the Count of Chinchón after an agreement with the villagers in 1586. There is a possibility that in this first visit he would have started the draft from the monastery (Marías 1980, 264–265, Marías 1986).

The contractors were linked to El Escorial, and it was there where the Specifications and documents were signed. The father Friar Antonio de Villacastín, who was assigned the correct interpretation of the Specifications, was the master of works in El Escorial, finished in 1584. Pedro Sánchez, with a similar task to that of Villacastín, had been the mason master, also in the construction of El Escorial.

These multiple connections with El Escorial, give an outstanding importance to this Specifications, which show the way of constructing and contracting in the period right after the ending of El Escorial monastery.

The construction process of the nuns' monastery of Chinchón was very slow, and the inauguration did not take place until 1653 by the 5th Count, Francisco Fausto, buried in the choir of the monastery.

It is know that by 1606 the construction works had already been initiated, and in addition, these works were also mentioned in the last will of Diego's wife in 1611 and 1613. There is a bill paid in 1619 to the masonry master Hernando de la Cruz, friend of all the builders who signed the Specifications and were also contracted in the works of El Escorial. Once the monastery was founded, it was occupied by nuns and there are records of the payments in the accounts book done in between 1654 and 1661 to fit some of the rooms, such as kitchens, dining room of the infirmary (Marías 1980, 258–259; Cuentas 1653–1685).

The chronological events related to the different counts and the main architectural works, which took place during the construction of the nuns' monastery, are briefly stated in Table 1.

SPECIFICATIONS ANALYSIS

The original transcription done by Fernando Marías has been used for this critical study of the Specifications. The text has been divided into versicles, numbered in Arabic numbers, and coinciding with the different paragraphs, except in the first part of the text where paragraphs are too long and therefore the subdivision has been shorter (Condiciones 1597).

General characteristics

The text is written in a direct style, with a concise prose, and with a language for experts in the construction trades. It is written without any didactic purpose, using the minimum necessary to fulfill its purpose. It details the rights and obligations of each party and fixes the procedures to solve the interpretation problems, measurements and bill of quantities. It describes the compound work units and fixes the prices for the piecework tenders. It corresponds to the documents we use presently in the construction practice in Spain, the Specifications and the bill of quantities. It is a concise and simplified example of the redundancy and sometimes overwhelming legislation that pervades present times.

The text does not have subtitles or subdivisions, although in general, each paragraph corresponds to a different compound work unit.

It is dated on July 26th 1597, and it refers to the construction of a nuns' monastery in Chinchón

Table 1. Chronology

Counts of Chinchón monastery	Architecture in Chinchón	Nuns
1480–1511 Andres Cabrera married to Dª Beatriz de Bobadilla, 1475 Marquis and marquise of Moya 1480 Lord of Chinchón	Convent of the Agustinians (late 15th century) 1499 first town hall placed in the same present location in the main square First castle construction (before 1521)	
1511–1522 Fernando, 3rd son, Lord of Chinchón, married to Teresa de la Cueva since 1520, 1st Count of Chinchón	Possible construction of the Palace	Founding wishes
1522–1575 Pedro Fernández de Cabrera y Bobadilla, 2nd Count, married to Mencía de Mendoza y de la Cerda	1534 Beginning of new church 1559–75, Castle construction for some authors	
1575–1607 Diego, 3rd Count married to Inés Pacheco	1586 Agreement between Count and townspeople to continue the construction of the new church 1593 Nicolás de Vergara visits the construction works of the new church 1598 Castle finished	1596 Stonework contract for the church body 1597 Specifications 1597 Masonry and bricklayer contract. Construction works begin
1607–1647 Luis Jerónimo, 4th Count, Viceroy of Perú (1629–41) married to Francisca Enriquez (La Chinchona)	1626 Construction of the new church finishes 1626 Removal of Agustinian convent to the present location of the Parador	1606 first news of construction works 1619 first news of payment for construction works done
1647–1665 Francisco Fausto, 5th Count, since 1640 1st Marquis of San Martín de la Vega. Married to Francisca de Cordoba y Velasco Not direct heirs.	1654–58 Worship in the new church, due to works in the old one	1653 Founding of the Monastery of the Order of St. Claire 1654–61 Improvement works
1665 Inés de Castro, 6th Countess 1665–69 Francisca de Cárdenas, 7th Countess 1669–83 Francisca de Castro, 8th Countess 1683–1712 D. Julio Sabelli, Prince of Albano y Venafro, 9th Count. Lawsuit for the succession Cayetano Esforcia, 10th Count José Esforcia Cesarini, 11th Count 1738 Sale of the County to the Infant Felipe, 12th Count 1761 Sale of the County to the Infant, Luis, 13th Count	1683 Main Square is closed completely 1668 Construction of the chapel of St. Roque 18th century Chapel of the Misericordia, initially chapel of the Hospital 1713 Church tower is rebuilt 1713 Main Square is opened again 1740 Palace destroyed	Burial of the 5th Count in the choir Burial of a son of the 13th Count in the choir.

without specifying the religious order for which it was built.

The construction is ordered by the Count of Chinchón, although it does not specify exactly who he is, not even in the signature (Condiciones 1597, 1, 34, 40, 42, 45). Inferring from the date we know that it is Diego, 3rd Count since the death of his father in 1575 until 1607.

The document refers to the drawing, plans and sections, by Nicolás de Vergara, signed also by the Count, which probably were attached to the document or were handed to the contractor masters. In the transcription of the document, it does not mention that the Specifications are also from this architect, although Fernando Marías, who has a lot of experience in interpreting this type of documents, has assumed so (Condiciones 1597, 1; Marías 1980).

The construction works are commissioned to three stoneworker and masonry masters: Juan de Eras, Pedro de Pedrosa and Juan de Bozaraiz, who sign the specifications together with the Count of Chinchón (Condiciones 1597, 34, 42, 45).

In two occasions, there are references to some specifications signed previously, which had been lost (Condiciones 1597, 24, 26). It seems, from the context, that those documents refer to the stoneworkers' work in the monastery courtyard.

In various places, the text distinguishes between the church masonry of, from the others in the rest of the monastery. At a certain point, it indicates that the church masonry is already agreed upon, and commissioned to Bozarraiz (Condiciones 1597, 12).

In the description of compound work units it follows the common logical order of the construction process, from the foundations to the roof covering.

There are advices and indications given to avoid possible conflicts with other trades. Therefore, a new plotting is asked over the trenches previously opened, before starting the foundation masonry (Condiciones 1597,2). Precise conditions for the materials supply and auxiliary means are given, both supplied by the Count. The tools and utensils are to be supplied by the contractor masters (Condiciones 1597, 40, 41). The time and place for fitting the collar beams in the masonry, needed for the carpentry work, are also stated (Condiciones 1597, 8, 10).

In relation to the work units, indications of their geometry are given, sometimes referring to the plans, and some other times referring to the commands to be given during the construction. In some other cases, in the simplest ones, a direct description with the measurements is recorded. The finishings are also included: the type of stonework in the ashlar and the renderings for the masonry. Measurement criteria are shown for the openings and the wallings. Also, prices are given for the different work units.

A system of appraisal of the works was established, done by two quantity surveyors: one chosen by the Count and another one by the contractors, and a third one from the trade named by law in case they did not reach an agreement (Condiciones 1597,12). The father, Friar Antonio de Villacastín and the surveyor Pedro Sánchez were named to solve the conflicts or doubts in the interpretations of the Specifications (1597, 34).

The beginning of the works was established for September of the same year (Condiciones 1597, 34), mentioning the costs and the tenders to be paid, with an initial payment on account (Condiciones 1597, 33, 34). A safeguard was included, which allowed the Count to contract building masters, officials and laborers, on behalf of the contractors' if they did not carry their orders out correctly, specifically according to number of workers in the construction and perfection quality of the works (Condiciones 1597, 42). Also, the document specified that in the event of an interruption of works due to lack of supplies — during six months— it was possible to clear the works done (Condiciones 1597, 44).

Masonry materials condition and masonry work units

The materials which the Count has to supply are listed: «stone, lime, brick, plaster, water, sand, shingles, mud for walling, timbers, nailings, roof tiles and stones to be worked». The document specifies that the materials should be supplied on site, providing easy accessibility for the transportation (Condiciones 1597, 40).

The ceramic bricks of the time were solid and had a large rectangular size, with an approximate proportion of 3 to 4. In the text, the dimensions are called «frente», head and «asta», stretcher. The head corresponds to the smaller dimension of the brick bed and the stretcher to the larger one ("frente» corresponds to the word *tizón* nowadays and «asta» is

called *soga*) (RL 1988). By the study made of the bricks used in the monastery, the workers used one foot for the header (barely 28 cm) and a quarter of a stick for the stretcher (21 cm).[4]

Regarding the conglomerates, the texts states that the lime should be supplied «burnt and sieved», whereas the dead lime should be made by the masters who should «slake, mix and beat» and soften it again when they are going to use it, fixing the time of this last preparation having in mind that it shall be «mixed and beaten twelve or fifteen days before its use» (Condiciones 1597, 40 41).

Regarding the work units following the normal order of the construction works, the different geometry sizes, finishing degree, as well as the measurement and evaluation conditions are indicated. We include the constructive conditions in the order they appeared, since they can give us a special insight into the masonry and stonework constructive processes in Spain in the late 16th century, in a place close to the construction of El Escorial.

The foundations should be leveled and plumbed, with lime and stone, with the required thickness, and up to the height of the ground floor (Condiciones 1597, 2).

Each masonry wall of the foundations, as well as the walls of the underground vaults shall be of two hundred square feet modules (10 in length by five in height by four in thickness)[5] (Condiciones 1597, 14).

Underground vaults shall be made with brick and lime, one foot thick, plastered and scratched on the part below. They will be constructed in modules or walls of fifty feet measured from the interior. The contractors, with timbers and nails supplied by the Count, will make the archway centerings. The third part shall be cladded and the other two filled with sand, provided by the Count (Condiciones 1597, 15).

The walls with the openings shall be constructed according to the plans and elevations, both for the thickness of the walls as for the length and height of doors and windows. The masonry walls shall be plumbed and leveled, using lime, stone and brick (Condiciones 1597, 3).

In relation to the openings, Figure 1, the «sides of doors and windows shall be built with brick pillars and brick arches».[6] The window sills should have one header in height and half a foot overhang.[7]

The splay shall have a rebate at the lower part coinciding with that of the jambs[8] to house the carpentry. It should have a rise[9] of half a foot

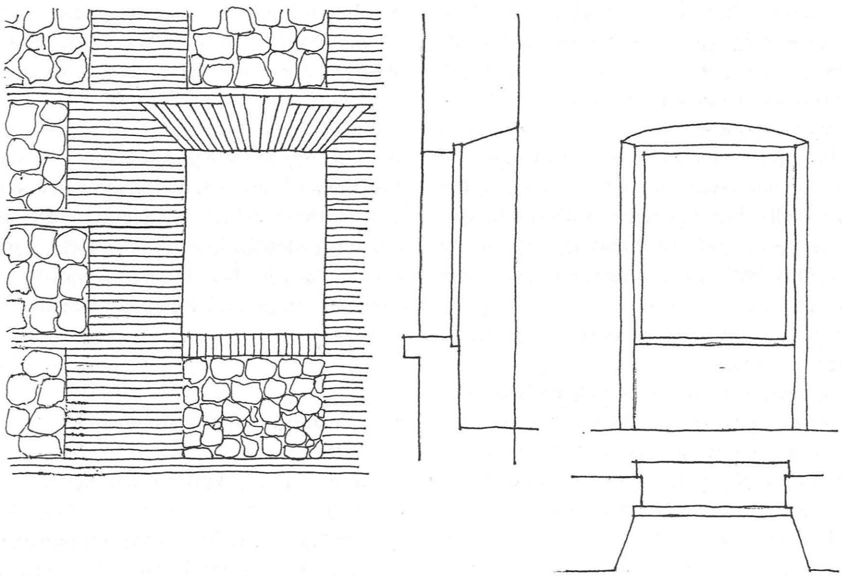

Figure 1
Wall opening, according to the description in the Specifications

minimum. The trabeated arch shall be one stretcher thick by one header high. The thickness of the splay shall be equal to the wall thickness[10] (Condiciones 1597, 5).

The pillars separating openings or between the walls shall be made of bricks with set-ins or steps.[11] In the set-ins the smallest part should have a width equal to that of the wall, and the greater part will project from the smallest part, one header on each side. The pillars should be always started by their greater side. Every four feet, they shall have a binding brick course, both in the openings, and in the mud and masonry walls. The binding brick courses, which have to be built between enclosures, are not considered (Condiciones 1597, 6, 7).

Once the first slab is reached, the collar beams will be set correctly leveled at the appropriate height (Condiciones 1597, 8.)

The walls shall be built after that, with their openings, up to the second slab, with the length, height and width according to the plans and elevations, and built in the same manner as in the previous case (Condiciones 1597, 9).

All the masonry, be it stone, brick or bonding[12] shall be made regarding the previous conditions (Condiciones 1597, 12).

For quantity purposes a module of enclosure of two hundred square feet is considered,[13] which would be the common dimension of the caissons. The walls shall be plastered and scratched inside and outside, both brick and stone (Condiciones 1597, 12).

The mud walls are also mentioned, high or low, which shall be three feet wide by four feet high and ten feet long, giving prices accordingly to whether they are black walls,[14] or concrete[15] walls on the two faces. The tie rows and the bondings are to be measured together with the corresponding wallings (Condiciones 1597, 16).

The vertical divisions are mentioned, made by double partitions (Condiciones 1597, 32).

The main arches of the church shall be built with brick and lime or gypsum[16] as ordered and must be three feet wide, including the width of the pillar and the projecting ridge. Included within the price are the scaffolding and the arch centerings, as well as the removal of the false arch. They must be measured from the interior part.[17] They must be left plastered, and whitewashed as well as finished (Condiciones 1597, 17).

The ridges must be set again at the height of the roof rafters and the roof chambers (Condiciones 1597, 10).

Bricks must be used for the cornices according to the plans except in the church exterior which shall be of stone, as is later specified (Condiciones 1597, 11).

The church vault must be of sardinel brick, three brick thick, plastered and whitewashed with white gypsum. They must be measured from the inside in squared sticks, and a thickness of one partition and two double ones (Condiciones 1597, 18). In the vault extrados, at both ends and every eight feet, one foot thick abutments[18] must be built, which will reach up to two thirds, packing the vault belly about two feet[19] (Condiciones 1597, 19).

If the vaults include fascias, they must be plain, without moldings or fillets, and must be measured in all their width and skewback, in squared sticks (Condiciones 1597, 20).

The prices distinguish between the «jaharrado»,[20] whitewash[21] and washing finishing,[22] differentiating whether the last one has been done with white gypsum[23] or with black gypsum[24] (Condiciones 1597,21).

Two ways of placing the tiles are distinguished. On the church roof, the tiles shall be placed «a cama llena»[25] with the channel tile doubled and rendered, «los lomos llenos»,[26] the ridges rendered and the roof pendant nailed. On the other roofs, the tiles must be fitted in the same way, but without nailing the pendant (Condiciones 1597, 22, 23).

Finally, the contractors shall supply the tools and utensils cited in the Specifications. The utensils, more than the tools are detailed, maybe due to the fact that it was there which problems arose more often. Therefore utensils like, «tool baskets, sieves bath box, wooden bowls, handbarrows, buckets, scaffolding, arch centerings and ropes are stated» (Condiciones 1597, 41).

Specifications for the stonework

When the text mentions the materials, which the Count has to supply, it indicates that «the stone shall be supplied dressed and «cajas rompidas»[27] according to the gages and molds given to the stoneworkers as it was the use in the stone quarry» (Condiciones 1597, 40).

The stone units refer to the courtyard façade and to the church cornice, with the hand drawing of the Count on the side, as well as to the generic units such as ashlar, plinth, and slabs.

The courtyard façade is composed by a series of arches and columns, with windows in the upper level. The stonework of the arches is described in detail, with its column, base capital and its brick spout, as well as the stone fascia over the arches, all of it according to the drawings. The openings for the upper windows are also detailed, with window jamb and lintels also made of stone. Although the type of stone is not expressed, the tools used for hewing, the axe[28] and the tooth axe[29] are detailed (Condiciones 1597, 24, 25, 26). The corner pillars are mentioned, indicating that « . . . the over sizing would be paid» (Condiciones 1597, 35)

For the church, the stonework units are also described. The exterior cornice of stone, according to the drawing on the side, mentioned above. The plinths or internal bases, with «work stones of one foot and a half in length[30] and half a foot in height», with its seen face axed and tooth axed, «it should be well dressed and perfectly fitted to be inside the church» And the slabs for the paving must be of «picón[31]» (Condiciones 1597, 24, 26, 27).

In three of the work units described, there are interferences with an earlier lost contract signed by the Count, to which the prices are to be referred in case it appears (Condiciones 1597, 24, 26, 27).

At last, generic prices are given of «any stonework . . . such as ashlar, plinths, and other things for such a work» hewed superficially with a small pick, to be used in any part of the work (Condiciones 1597, 28, 39).

Bill of quantities

Together with the working specifications, several criteria for surveying and plotting are given. The units for measurements are the foot and its submultiples: half a foot and a quarter foot. The stick is also used, which equals three feet.

In masonry, to measure the volumetric units, a reduction to superficial units is made, considering the common thickness of 3 to 4 feet. Therefore, units of 200, 120 or 50 square feet or surface units are used, coinciding with the common units for enclosures. There are also valued by thousands, when dealing with the tile placing.

In stonework the tendency is to reduce the unit to linear units, using the stick, or calculating by the work units

The unitary prices are given in «reales», half «reales» and «cuartillos», as well as in «ducados».

Unitary prices for laborer's piecework are shown on table 2. The figures have been obtained from the Specifications, and expressed in the modern way, unifying the units to feet and the prices to «maravedies»,[32] so as to compare them. (Font 2000).

Comparative analysis with the existing work

Two main elements of great interest are considered in this analysis. The Northern wall, which is the exterior enclosure, and corresponds to the sites occupied by the sacristy, church, choir and novitiate, and the cloister façade, considered of great singularity by all the different critics (Marías 1980, 263; Serrano 2000, 69) Fig. 2.

Regarding the materials used, white limestone of Colmenar de Oreja is used, which was a commonly used stone in Chinchón, extracted from the nearby quarries. Nevertheless, it is not specified in the Specifications document the type of stone to be used, as the Count would supply it.

Northern façade of the monastery

When studying the Northern walling, the constructive change at the cornice level of the choir strikes our attention. In fact, under the cornice, stonework is used for the plinth, corners and voids packing with ashlar and random rubble, cyclopean in the lower part and of medium size in the upper part. Nevertheless, the body of the choir and novitiate is crowned with a brick cornice and from that level upwards, the walling is made of masonry, with the corners, void packing and cornices made of brick and the rest with mixed bond or bond in the style of Toledo with piers ranging from bigger to smaller and brick rows underlying the stone masonry blocks of rubble stone and medium sized, similar to the upper masonry of the quarry area (Figure 3).

Table 2. Bill of quantities for the work units contracted in the Specifications
Listing of the trade tenders obtained from the bill of quantities cited in the Specifications. So as to standardize and make comparisons, the prices are given in maravedíes and the units are reduced to feet, square feet or cubic feet. The prices refer to the construction work only, since the materials were supplied by the owner.

Unit of measurement Masonry	Description of trade work	Price in *maravedises*
Cubic feet	Wall of stone masonry, or of any brick type, in modules of 10 feet in length, by 5 feet high and 4 feet thick, in foundation or wallings, rendered and stripped on both sides, measured all along (openings included as solid), intermediate rows included.	2,75
Cubic feet	Black earth walling in modules of 10 feet in length, by 4 feet high and 3 feet thick, in any type of walling, rendered and stripped on both sides, measured all along (openings included as solid), intermediate rows included.	0,85
Cubic feet	Concrete walling on both sides, in modules 10 feet long, by 4feet high by 3 feet thick, brick rows included.	1,13
Cubic feet	Concrete walling on one side, in modules 10 feet long, by 4feet high by 3 feet thick, brick rows included.	0,99
Squared feet	Double partition wall, for vertical divisions, neither plastered nor rendered.	2,89
Squared feet	Underground vault walling of brick and lime of one foot thick, rendered and stripped on the lower part, and cladded at the bottom third part, and also the proportional part of the arch centering measured from the interior part.	14,96
Linear feet	Main arch, 3 feet thick, measured by the internal part, with its total width of 3 feet projecting part included. Rendered with black gypsum and whitewashed with white gypsum. Proportional part of scaffolding false arch and mounting and dismounting included.	283,33
Squared feet	Brick vault of 3 feet in thickness, rendered in black gypsum and washed and whitewashed in white gypsum, measured from the interior. It also includes the proportional part of the abutment, one foot thick every 8 feet long on both sides of the vault up to 2/3 in height, and compaction of the spandrel up to two feet.	32,11
Linear feet	Flat outstanding fascia over the vault, without moldings nor fillet, measured throughout the width and with the protrusion specified, for a widthness of 3 feet.	14,05
Squared feet	Black gypsum rendering and washing and whitewashing with white gypsum over any type of walling.	3,40
Squared feet	Black gypsum rendering and plastering and washing with black gypsum over any type of walling.	2,72
Squared feet	Black gypsum rendering over any type of walling.	1,36
Unit	Tile fitting packing, including proportional part of channel tile doubled and rendered, filling, compacting and rendering of ridges.	1,02
Unit	Tile fitting packing including proportional part of channel tile doubled and rendered, filling, compacting and rendering of ridges, and also proportional part of nailing of the eaves.	1,50

Table 2. Cont.

Unit of measurement Stonework	Description of trade work	Price in *maravedises*
Unit	Arch with its corresponding plain pillar, base and capital, according to the project, all worked in stone, hewed with axe and tooth axe, placed, including the brick mouths which are in the extrados of the arch, up to the stone fascia, and also the paving under the arches, projecting a little over the width of the base.	8.812,50
Linear feet	Stone fascia, hewed with axe and tooth axe, with protruding parts and height according to the section plans, over the previous arches.	39,66
Unit	Stone balcony opening with its jambs and lintel having all the thickness of the wall, hewed with axe and tooth axe, according to the plans, including interior and exterior caissons and projecting parts.	3.264,00
Linear feet	Church external stone cornice, according to plans, measured along the length of the mouchette.	204,00
Squared feet	Ashlar stonework, parapets, plinths, and similar parts, except jambs and lintels, hewed plainly with small point with a height of $^1/_2$ feet, measured from the exterior.	11,33
Squared feet	Plinth with ashlar of 1 $^1/_2$ feet long and 1 $^1/_2$ feet high, in the inside of the church, finely hewed with axe and tooth axe and tightly placed, measured by the protruding parts.	22,66
Squared feet	Plinth with ashlar stones 1 $^1/_2$ feet long and 1 $^1/_2$ feet high, picked.	18,88
Linear feet	Picked stone slabs for the church floor, measured in length, with whatever the width they have.	17,00
Squared feet	Stone ashlar hewed with axe and tooth axe with a seen surface of 4 $^1/_2$ feet, outside the church plinth.	18,88

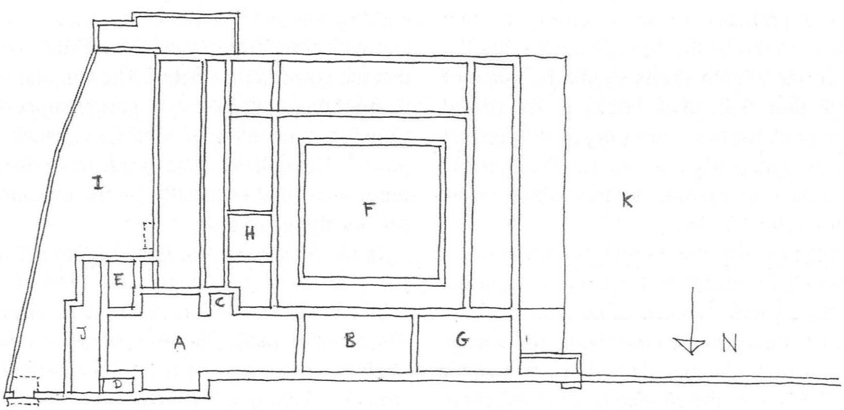

Figure 2
Monastery of the Inmaculate Conception, of St. Clare nuns, in Chinchón. Plan of the whole building. 1) Church, b) choir, c) chapel, d) sacristy, e) new choir, f) courtyard, g) novitiate, h) staircase, i) access porch, j) janitor's house, k) vegetable garden

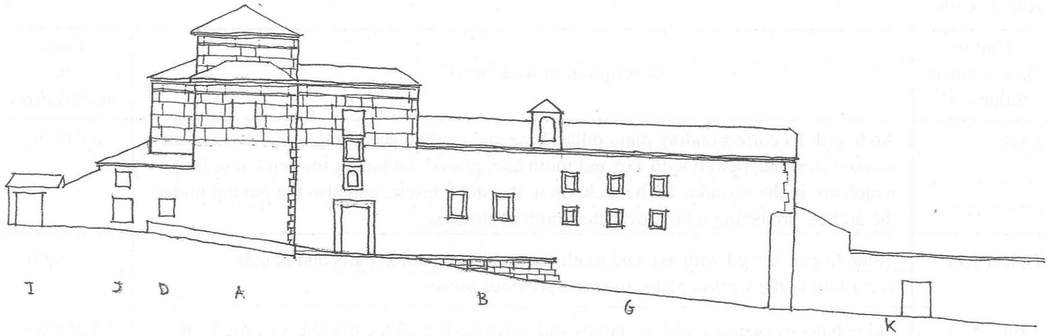

Figure 3
Nuns' monastery of Chinchón. Northern façade to the exterior of the enclosure

This change in the type of walling, probably to decrease the costs, is already mentioned in the Specifications. It incorporated a bricklayer and the corresponding working units, in the piecework, whereas in the first contract referring to the body of the church, it was made exclusively by a stoneworker. On the other hand this will be the general trend in the 17th century in Spain.

In the Specifications, the beginning of the construction is not mentioned, although nothing is said either about the opposite. A project of Nicolás de Vergara is mentioned as well as the existence of a previous bidder for the piecework of the stonework in the church body. Up to the level previously mentioned, the Northern walling was made of stonework, and probably made according to that piecework. It is stated in the Specifications that the construction of the church vaults should be made of masonry, with three feet thick bricks in the ribbed arches and the brick sardinel vaults made of three feet thick bricks, as apparently was made. That greatly reduced the prices in relation to the ashlar vaults (Specifications 1597, 17, 18).

It is difficult to verify the correct execution of all the work units. It is clear that it was not carried out correctly in the church cornice, since it is made of brick instead of stone. On the other hand, the change from the stonework to the mixed bond masonry in the church body, built from the cornice level of the choir, was not planned in the Specifications. It looks like a simplification to make equal with the other walls of the monastery, described with several different types of masonry, the mixed bond or Toledo style included (Specifications 1597, 6, 7, 13).

It is also to notice the important inclination of the crowning stone fascia of the plinth in the church adapting to the slope of the site, using a bad constructive solution, as opposed to the leveled foundations of the Specifications. Maybe this was so because they corresponded to the body of the church previously assigned[33] (Specifications 1597, 2). In the choir plinth the defect is corrected and the voids corresponding to the foundation vaults are shown. In the novitiate area, the ashlar plinth disappears.

This different treatment of the plinth throughout the Northern façade, can only be justified, because it corresponds to different parts of the body of the building, probably built in progression to the West and with time differences, during the two long years that the construction lasted. The singular crowning of the building in the Western corner supports this idea, showing an intention of continuity, which did not take place.[34] Nevertheless, the façade has a distinguishable unity, produced especially by the masonry treatment previously mentioned.

In the Specifications, there are no norms given for the stone openings in that façade. Probably it will have been a modification done after the construction works. The window sills, jambs and lintels built project slightly from the façade, which would allow the masonry rendering,[35] announced in the Specifications (Condiciones 1597, 13). Its simple but correct carrying out, with an upper discharging arch and lintels with small side projections, parallels the voids of the

Chinchón castle. The openings of the choir plinth are uneven though being very closed to each other. The left one with the adornments standing out, and the right one, of a smaller height, leveled up with the wall corresponds to a crypt under the choir, covered by a barrel vault with different cells for each opening.[36] The two openings of the choir are rectangular, and the ones of the novitiate area are quadrangular and placed in two levels, three on each level.

The church portal is not mentioned either in the Specifications. The door is made of simple ashlar, in line with the openings previously referred to. The jambs and lintel of one stone, slightly overhanging from the façade wall, made of ashlar near the opening, with a flat discharging arch the threshold also one stone, overhangs a little more than the jambs. These all indicates, that the stonework, except for the adornment of the openings, was prepared to be rendered. Over the door is a brick niche with a simple design, and over it we can find a superb marble coat of arms,[37] with the arms of the Cabrera and Bobadilla family, and the small shield of two cauldrons, over the St. Jacob's cross with a crown at the top, similar to that of the castle. The small shield with the two cauldrons corresponds, according to Cooper (1980, 700), to the arms of Inés Pacheco, wife of Diego the 3rd. count of Chinchón. Therefore, the coat of arms corresponds to this count.[38] Over the monastery entrance door, by the Southern porch, protected with a small roof, there is another coat of arms, with the same motif, but smaller and made of sandstone or limestone.

The masonry church openings have the jambs made of bricks, they lack any type of sills, and are directly supported by a masonry caisson and crowned at the upper part with trabeated arches made of brick, slightly pointed at the keybrick position, a characteristic of a masonry of early baroque style. It was carried out according to the Specifications for the openings, jambs and crownings.

The cornice of the body of the church, and the corresponding one of the choir and the novitiate, are very similar, made of brick, in successive rows, with a quarter brick bead sardinel coarse of pressed bricks and as crowning another header brick row.

The masonry corresponding to the body of the sacristy, which fits into the floor plan in the overhanging left by the transept, is intended to combine with the rest by using stonework masonry, but it lacks a plinth in some parts, as well as lacking ashlar opening and cornice adornments. Therefore, it could well be a later addition.

Regarding the interior church plinth, it can be seen that it corresponds with the Specifications, although it is two feet high instead of one and half as stated in the Specifications. Nevertheless, the paving proposed in the Specifications does not exist: or it was never built, or it has disappeared.[39] There is only one perimetral stone border, at the level of the pavement, which could have belonged to a stone paving at the encounter of the wallings or at the foundations crowning as support to the plinth.

Courtyard façade

In this enclosure wall, the Specifications are strictly followed, and therefore, we can assume that the project by Nicolás de Vergara was followed too. Figure 4.

From a constructive point of view, it is interesting to note the intelligent combination of stonework and

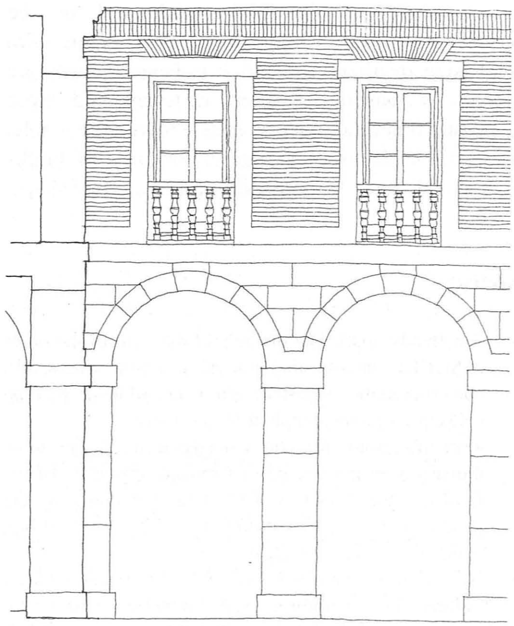

Figure 4
Nuns' monastery in Chinchón. Courtyard

masonry, in order to solve the enclosure of the upper cloister.

The arches and pillars with its bases and plain capitals, in the lower floor, are worked in stone of Colmenar, preserved in good conditions. Nevertheless, the mouth of the openings, which built in the extrados of the interior arches are made of brick according to the Specifications. Presently, the openings have been closed with wooden framed windows and doors and brickwork rendered externally and plastered internally.

As the specifications indicate, a stone row crowns the lower part of the building. Over it, openings with stone jambs and lintels, slightly standing out of the brick parament are laid, in line with the arches. The opening disposition is that of a balcony, but nowadays it has a walled up parapet made of masonry with a stone cladding serving as a window. There is testimony of the balustrade up to recent times, because of the open caissons at the jambs to fit in the sleeper and the top rail, as well as from some of the balusters re used now as handrails at the choir tribune. The wallings between the jambs are made of seen brick and their joints, in a more intense red are clearly defined at pointings and perpends. It may be the «work of joined in brick» indicated in the Specifications (1597, 37). Over the stone lintels, with small side overhangings, brick trabeated arches are placed. A masonry cornice, different and more elaborated than the exterior ones, crowns the whole. It is built with an overhang sardinel row of bricks with a soffit, and over it another row in an ogee shape.

NOTES

1. We greatly appreciate the help of the nuns of the order of St. Clare and especially the Abess for her kindness in our visits to the monastery, allowing and helping in the collection of data and photographs taken.
2. «Specifications for the Construction of the nuns monastery in the village of Chinchón by order of his Lordship the Count of Chinchón complying to the plans, sections, and elevations signed by his Lordship, made by Nicolas de Vergara».
3. Nicolás de Vergara, el Viejo (1517– 1574) was a master builder and sculpturer, glass window master and sculpture master of the Cathedral of Toledo, since 1542.
4. The foot of Burgos, or Castillian foot was 27,873 cm long. Phillip II unified the different dimensions coexisting at the time in Spain, in order to coordinate the work of El Escorial, Each stick was three feet long, that is 83,619 cm. The stick was divided in four quarters, therefore each quarter was 20.905 cm long.
5. Instead of using cubic feet to measure the walls, a modular wall of two hundred square feet was used, which equals four juxtaposed walls of 5 × 4 × 1 feet.
6. A masonry opening is described with its pillar jambs or brick pillars and the lintel built with trabeated arches and splays of the same material.
7. Literally, «los alfeizares serán de un frente de ancho y medio pie de salida».
8. The texts says: «el arco o el capialçado que tenga diente a la parte de abajo conforme al pie derecho» Condiciones 1597, 5)
9. The text literally says «Capialçado», that is elevated at the head. The word «capialçado» refers both to the geometric figure that crowns the upper part of an opening when the external part is more elevated than the internal part, as in the arch rise.
10. Literally «y tenga de grueso el arco o capialçado una *hasta* y una *frente* de alto y el ancho del grueso de la pared» (Condiciones 1597, 5)
11. This masonry is called literally as «pies derechos (studs) and are «de mayor y menor», of greater and smaller. «The smaller will be the wall width and the greater, the head bonding» (Condiciones 1597, 6)
12. In the text, the word *rafa* is used, that is, bonding made with rubble and gypsum, placed in between the mud wall units, curved on the side.
13. Ten feet long by five feet high and four feet wide, which cover two hundred square feet and one foot thick, equal two hundred square feet mentioned.
14. Black walls: Mud walls
15. Concrete: Paste composed by small stone, lime and bitumen, which lasts endlessly. It is also made without bitumen (Rejón 1788, 120)
16. The alternative stated between lime and gypsum seems very interesting, to fit the three feet wide brick, onto tan important part of the structure such as the main arches.. The final decision is left to the builder who shall determine and value the specific circumstances in order to choose the most appropriate one.
17. Literally it says «çintel». It may be referring to the *cintrel*: the rope or stick used in the centre of the vault in order to arrange and rebuilt the brick rows. (Rejón 178, 60)
18. Abutment: arch abutment, which receives the thrust of the building.
19. The arch abutments stabilize the thrusts of the barrel vault, produced in the spandrels.
20. Jaharrado: First coat of interior finishing, equivalent to rough rendering, usually made with paste or black gypsum mortar.

21. Whitewashed: Finishing coat of the interior rendering, equivalent to fine plastering, made with white gypsum paste. It can also be made with black sieved gypsum, passed through a very fine sieve.
22. Washing finishing: Finishing coat by means of a humid cloth. From the text, it is implied that it is done over the whitewash or plastering.
23. White gypsum: traditional gypsum made by calcinating crude gypsum and crushing the stones finely, selecting the best burnt and the whitest.
24. Black gypsum: traditional gypsum manufactured by calcinating crude gypsum and coarse crushing the stones, adding the ashes and remains of the calcination giving it a greying colour.
25. Set «a cama llena» is an expression, which means that the channel tile should be fitted with mortar over the board.
26. Lomos llenos: This expression seems to indicate that the cover tile must be packed with mortar over the channel tiles.
27. Cajas rompidas: It may refer to the insertions in the hewed stones, possibly to facilitate their transportation.
28. Axe: hammer like tool, with two cutting edges for hewing (Rejón 1788, 96). It is used with one hand and the cutting edges are horizontal, producing lines when hitting the stone.
29. Tooth axe: iron tool with two vertical indented cutting edges, with a wooden handle that could be used with both hands.
30. Bed: upper horizontal side of a workstone, perpendicular to the wall face, over which the next row stands.
31. Coarse dressed with a point.
32. A *maravedí* is a counting unit (it was not a coin) since the time of the Catholic Kings, and it includes the whole period considered. The *real* is a silver coin, which valued 34 maravedíes. The *ducado* was a gold coin of 23.5 carats, which was equivalent to 375 maravedíes. In 1537, with Charles V, to homologue with the European coins, the *escudo* was introduced, which was a gold coin of lesser value, 22 carats, equivalent to 350 maravedíes. And later, in 1604 up to 440 maravedíes. Nevertheless in the Specifications, the currency cited is the *escudo.* (Font 2000).
33. Right at this place there is a failure in the foundation, which causes presently many important damages.
34. Maybe it is related with the remains of a bay in front of the Western façade which had not been finished.
35. On the Eastern façade of the monastery, there are remains of this rendering, which would confirm this idea.
36. All of this shows the initial surveys at the foundations level, something similar, although in a smaller proportion to what happens in the basements of El Escorial.
37. It has a white bluish marble frame and the main part in white marble. Unfortunately, the overhanging crown, at the top, is broken. Its stonework is much finer and with more baroque adornments than the coat of arms located in the castle. It has not got the Isabelinian eagle which crowns the one at the castle.

The sculptural group of the grave of Francisco Fausto, the 5th. Count, situated at the back wall of the choir, has a crowning of a shield held by two angels, but the two cauldrons do not appear. The sculptural remains of the burial , presently very destroyed, are of a very fine stonework, made in white marble. Apparently they were made in Italy with Carrara marble.

38. Nevertheless, the scene of the exterior coat of arms is more related, possibly, to the burying of the 5th. Count.
39. The nuns have told us that in the recent works done to install the air heating, under the floor of the church, no remains of stone paving have appeared. The present paving is of terrazzo tiles and was laid in between 1961 and 1964.

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The appearance of trusses in the Low Countries

Dirk J. de Vries

Stone buildings of the Romanesque period might still contain original timber parts. These early wooden constructions of floors and especially carpentry are starting point of a development leading to the application of trusses in the 13^{th} century. Thanks to dendrochronology it is possible to discover the first examples and have a closer look at the type of buildings and the regions in which these trusses emerge. Though the «package» consists of protective, supporting stone walls, the construction of timbers belongs to the craft of carpenters. As soon as we begin to find written evidence, the skill of wood-working is highly specialised already and master carpenters travelled widely in search of timber and notable commissions.[1] Mastering a craft like carpenter took years, may be decades of apprenticeship, oral training and learning by practising. Much of this mediaeval process remains a mystery because of a lack of written information and therefore becomes a degree of secrecy. Little changes in this co-operative system of working and training: comparable constructive solutions and similar materials in place and time occur. However, minor or far-reaching changes took place. Do we talk about evolution or invention as ways of change? Do internal improvements, ideas from outside, new tools, different materials or demands of other crafts cause them? Though interesting, different types of assembly-marks, the use of purlins in stead of plates, belongs to the minor changes in roof constructions, unlike trusses. Trusses differ in size and place from the rafters they support. They are primer frames, spaced at about 2 till 5 meters interval, newcomers and successors of the earlier common rafter roof. In the Low Countries their introduction took place in the 13^{th} century, first and most independently in the south, gradually and later, more as part of the rafter roof, in the north during the 14^{th} century.

Continental studies of carpentry appeared in Germany in 1908 (Ostendorf), 1980 (Mennemann) and 1991 (Binding), in France in 1875 (Viollet-le-Duc) and 1927 (Deneux), as in Belgium in 1995 (Walloon provinces in Belgium, Hoffsummer). Herman Janse, an active member of the Netherlands Department for Conservation (Rijksdienst voor de Monumentenzorg, RDMZ) published his main work about roof framing in the Netherlands in 1989. Previously, in collaboration with the Belgian Luc Devliegher, Janse had presented an important article about shared timber heritage in the Low Countries (1963). Janse's elaborate typological investigation, comparable with those formulated by C. Hewett and others in Britain, can now better be dated thanks to a series of dendrochronological investigations which I have carried out for the RDMZ since 1984. In a small country like The Netherlands there are remarkable differences in the «development» and diffusion (as far as this might be considered an autonomous process) of roof construction. In this contribution I try to find a relational context and the connections with

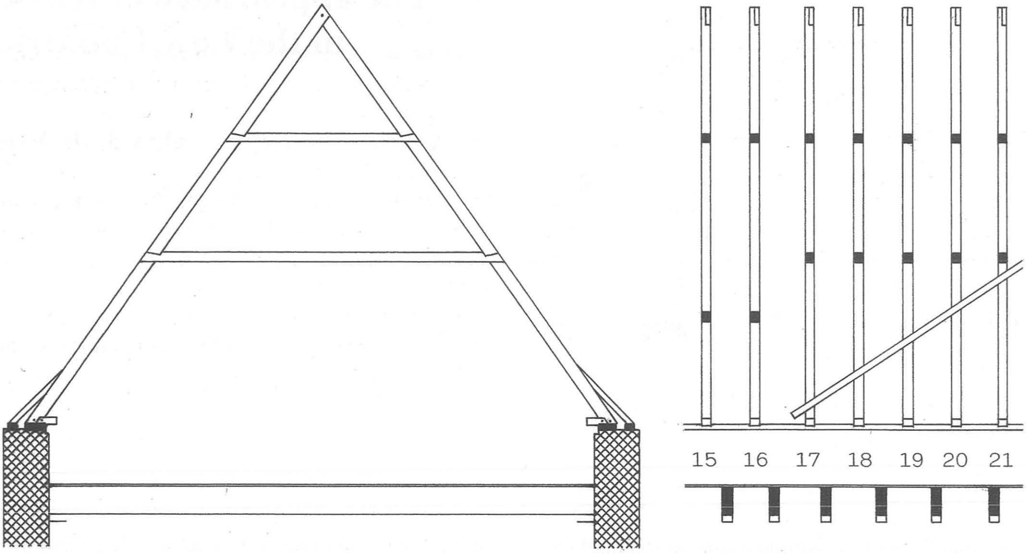

Figure 1
Drakenburg House, Oude Gracht 114 Utrecht 1291 (d). (Drawing L.M. de Klein RDMZ)

floor and wall structures for the oldest trusses in roofs.

The Common Rafter Roof

Throughout the Netherlands no evidence of timber roof construction prior to the thirteenth century has yet been found. Like elsewhere in Europe, the most basis form, the pure single rafter roof, is practically timeless: this type occurred in towns up until the fourteenth century and the countryside in the following centuries. Common rafter roofs can be found on houses in the town of Utrecht, built around 1300 with timber for rafters and collars of South-German fir with rectangular cross-section (Abies Alba) in addition to smaller pieces of oak for curved parts and at the bases in connection to the walls. The couples of rafters are erected on double wall plates and, at a right angle to them, on a sole-piece in which each rafter and a vertical post, the Ashley-piece, are jointed with a mortice-and-tenon. Drakenburg House (1291 d) and Te Putte House (1309 d) both merchant and warehouses situated on the Oude Gracht (Old Canal) have roofs built in this way in combination with thick brick walls and single floor joists, Figure 1. The number of collars vary from one to three, like the roof of the (not dendrochronologically dated) Dean's chapel of St. Peter's church in the same town with two collars. There is no fundamental difference between these common rafter roofs on houses, churches or other types of buildings. Though, church roofs often have wider spans and special solutions, either for a spacial or a constructive purpose. Such a variation of the common rafter roof with curved braces for a boarded ceiling, giving the effect of a barrel vault, like St. John's in Utrecht has (1279 d), Figure 2. The spacial advantage of this type of roof construction is that the interior of the church looks higher by integrating the roof (loft). The region in which the wooden barrel-vaulted ceiling was used as a specific architectural style for churches in the Netherlands extends in the west along the sea cost.[2] In the oldest (church) roofs every couple of rafters had its own tie-beam, like those of Our Lady's in Maastricht (reconstructed, 1219 ± 5 d), Figure 3. In order to avoid sagging of the tie-beam, a number of hanging post is added. Though roof constructions of that type and age are rare in the Netherlands, we find them in France and Belgium dating back to the 11[th]

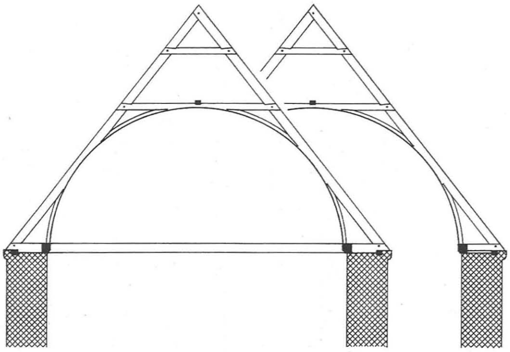

Figure 2
Nave and transept of St. John's church in Utrecht (1279 d). (Drawing L.M. de Klein RDMZ)

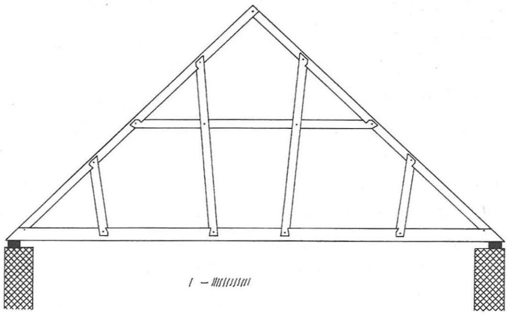

Figure 3
Our Lady's church in Maastricht, reconstructed triangel of tie-beam and a pair of rafters, 1219 ± 5 (d). (Drawing L.M. de Klein after H. Janse RDMZ

and 12th centuries.[3] In the last quarter of the 12th century, probably due to the apparent economy in the use of timber, one or may-be even a next tie-beam belonging to a pair of rafters was left out, presumably to save on wood. We find this clever solution not only in France but also in Belgium: Soignies (Saint-Vincent 1185–1200 d), Ename (Saint-Laurant 1175–1185 d) and Huy (Saint-Mort 1230–1235 d).[4]

Later on in the 13th century tie-beams only occur under every fourth, fifth or sixth etc. pair of rafters, Figure 4. The sole-pieces of the rafters in between are joined by a horizontally tenoned piece. These sole-pieces have the appearance of reduced tie-or foot-beams. Though we are still talking about common rafter roofs, in this system tie-beams tend to become concentration points of forces, here often in corporation with a single hanging post. In between we find pairs of rafters with reduced tie-beams, sometimes reinforced by scissor braces. The rafters sometimes show an alternation. In the north hall of Saint John's hospital at Bruges there is a common rafter roof of oak wood (1268 d) with two collars and alternating smaller and bigger rafters, Figure 5.[5] The smaller rafters are half as wide as the bigger one's which have a square cross-section of 18 × 18 centimetres. Though, regarding common rafter roofs in combination with single floor joists and

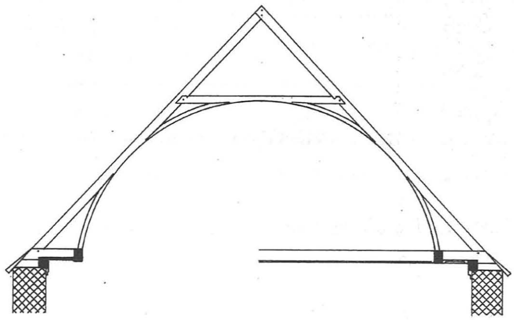

Figure 4
Oirschot, Boterkerkje, roof with barrel-vaulted ceiling of the 13th century. (Drawing L.M. de Klein RDMZ)

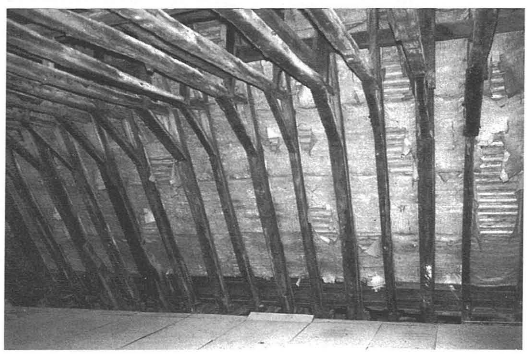

Figure 5
North hall of Saint John's hospital in Bruges, 1268 (d). (Photo by the author 1999)

Romanesque architecture, around the year 1200 this carpentry reveals a tendency of concentrating forces in main rafters with tie-beams, finally leading to the Gothic way of constructing.

The appearance of trusses

The oldest rafter roofs with trusses date of the 13th century. In the Netherlands they are present in the very south in two mendicant order churches at Maastricht. These are the roofs covering the choirs of the Dominican, Figure 6, and Franciscan churches, which date to 1277 (d) and 1305 (d) respectively. We find the horizontal truss beams joined with pegs to the rafters under they are placed, and bear similar number/assembly-marks. In a way these trusses can be regarded as part of the common rafter roof, a logical next step in the development of junctions with a concentration of forces. However, we do find a new element: a threefold of longitudinal plates resting on the trusses and supporting the lower row of collars. These plates concentrate the loads in the trusses, point

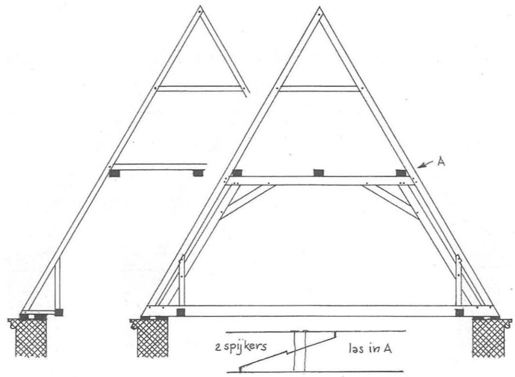

Figure 6
Choir of the Dominican's church in Maastricht, 1277 (d). (Drawing L.M. de Klein after H. Janse RDMZ)

where the carpentry gives its weight to the sidewalls, here reinforced by buttresses (in the Gothic system).

To the west of Maastricht, in Flanders (Belgium), a number of older trusses recently has been discovered.

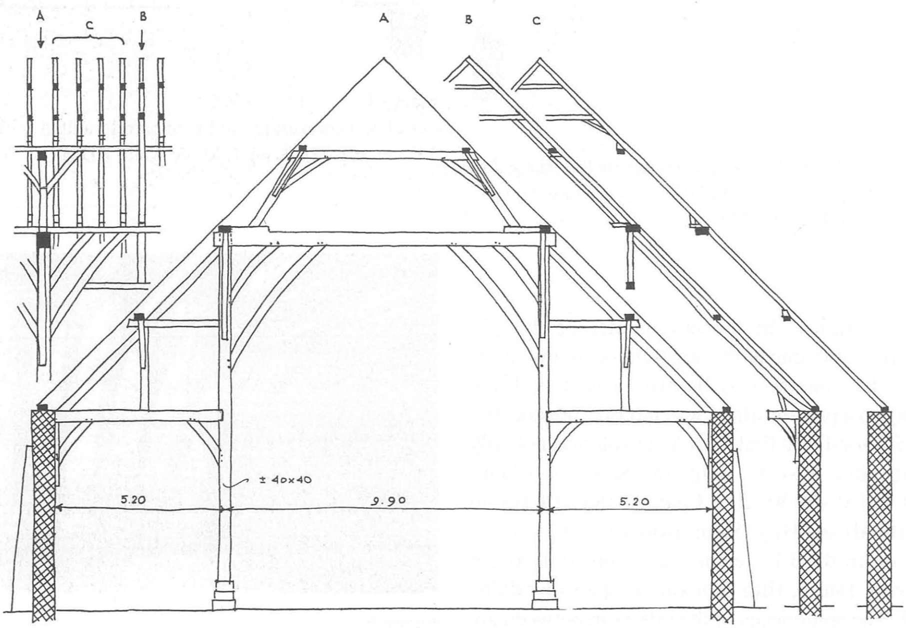

Figure 7
Lissewege (Belgium), barn of Ter Doest monastery, 1274–1294 (C14)

Several dendrochronologists attempted in vain to date the magnificent Cistercian barn of Ter Doest, near Lissewege in a polder to the north of Bruges. Here the timberwork consists of trusses on stone bases with a double bracing in both directions and a roof with single trusses, Figure 7. A closer look in the year 1998 revealed that both portal and roof trusses bear similar carved assembly-numbers, independently from the numbers on the rafters.[6] Compared with the examples mentioned before, and trusses of a later period, this is a «modern» feature. A fairly accurate radiocarbon date places the timberwork of Ter Doest in the years between 1274 and 1294.[7]

The double barrel-vault (without a boarded ceiling) of the Bijloke hospital in Gent with a span of 16 meters reveals big trusses without tie-beams, documented and dated in 1251-1255 (d) by Patrick Hoffsummer, Figure 8.[8] The oak wood was imported from the Meuse valley; between the trusses we find seven main rafters in alternation with smaller one's. Only the span of the former Knight Hall of the Binnenhof in The Hague counts more than 19 meters but the present construction (also without tie-beams) is a reconstruction of the mediaeval roof. Thanks to original timbers in the flanking turrets we assume that the main roof also dated in 1288 ± 6 (d).[9]

Janse and Devliegher already compared the Bijloke roof with the construction of the middle hall of Saint John's hospital in Bruges.[10] It was a great surprise to find out that the seven meters high trusses in the oldest part of this hospital date back to 1234 ± 6, Figure 9.[11] The façades and sidewalls are made of natural stone and brick; they contain single and double windows covered by round arches, Figure 10. Comparing the masonry of the window arches and the timberwork there is a striking contrast between the «old-fashioned» outside of the central hall and the trussed roof at the inside. Though the south (1285 d) and north hall (1268 d) both have relatively big, pointed (Gothic) arched windows, both have (slightly) different common rafter roofs. So, it seems

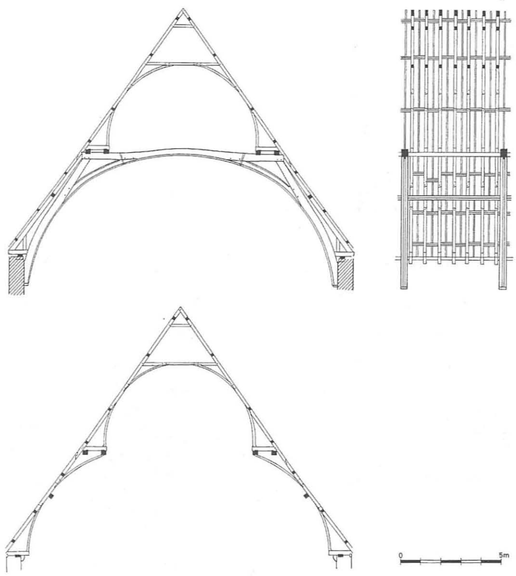

Figure 8
Gent, Bijloke hospital 1251–1255 (d). (Drawing Patrick Hoffsummer 1995)

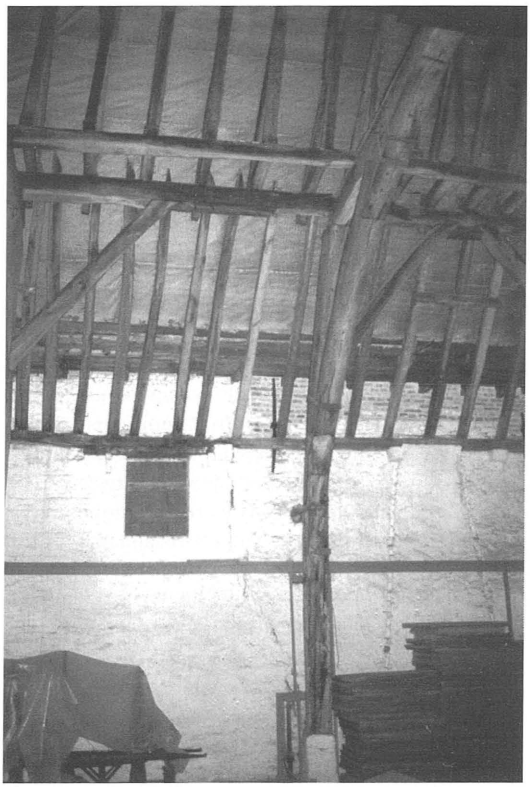

Figure 9
Saint John's hospital Bruges, roof construction of the middle hall, 1234± 6 (d). (Photo by the author 1999)

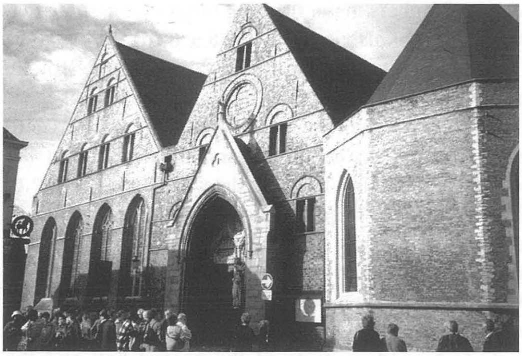

Figure 10
Saint John's hospital Bruges, front gables with south aisle (1285) on the left, middle part (1234 ± 6) with entrance under portal and to the right a chapel added to the north hall (1268). (Photo by the author 1999)

that not an architectural or stylistic reason lead to application of trusses in the central hall. This might be related to the span of the room: 12,6 meters, much more than either the north or the south hall.

For this moment the trussed roof seems to origin in Flanders: we do not find comparable early roof constructions to the south or north. A reflection on the diffusion can be traced to the north of the main rivers Meuse and Rhine. The trussed roof on the Knight hall of count Floris V in The Hague is the only example dating before 1300. The main building of the hospital of the Teutonic Knights in Utrecht, dating back to 1347 (d), has a barrel-vaulted common rafter roof without tie-beams or trusses.[12] In the episcopal capital Utrecht we find the first trussed roof on Leeuwenberg House, Oude Gracht 307 and dates to between 1319 and 1325 (d), Figure 11. It is worth mentioning here the use of both fir for long, strait parts and oak for the sole-pieces and the curved parts. As in the choirs of the mendicant order churches in Maastricht, the horizontal trussbeams are joined with pegs to the rafters under they are placed, and bear similar assembly-numbers. Only in the course of the fourteenth century carpenters in north started to number the trusses separately from the rafters. The earliest surviving instance of the separate numbering of trusses and rafters occurs in the roof of the church tower at Oudewater, dated to between 1336 and 1343 (d).[13] In this tower we find relatively high trusses (which seems to be an early characteristic) bearing three longitudinal plates. Other features of the 14th-century roof construction can be seen in the coupling of the principal and the wall plate via a short beam with a mortise-and-tenon in the principal; the same is done with the windbraces in the principals. The arrival of trusses brought with it the practice of adding a separate mark to the assembly-numbers on one side of the construction. This extra mark can come in the shape of a «<», a «fish», an «arrow» or an added square stripe (also called Flemish mark).

Though in the eastern provinces of the Netherlands the common rafter roof first seemed to be influenced by the application of a central reinforcement frame called «Stehender Stuhl», however soon by or in combination with trusses, like in the town of Deventer (and other like Zwolle, Zutphen and Arnhem). The house Bergschild 7 in Deventer shows trusses in the lower part of the roof and a central, longitudinal frame in the attic, Figure 12. During the 14[th] century a uniform system came into being by which the two opposite sides of a truss or rafter could be distinguished, for instance number three on one side was written as /// and the other side as //< or <<<.[14] Early examples of this system can be seen in the roof of the nave of the Bethlehemkerk in Zwolle,

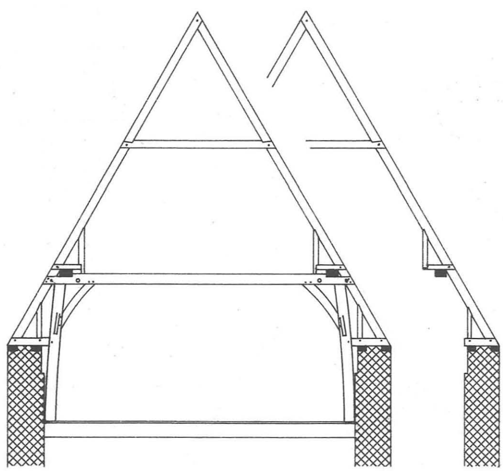

Figure 11
Roof construction with trusses in Leeuwenberg House, Oude Gracht 307 Utrecht, 1319–1325 (d). (Drawing L.M. de Klein RDMZ)

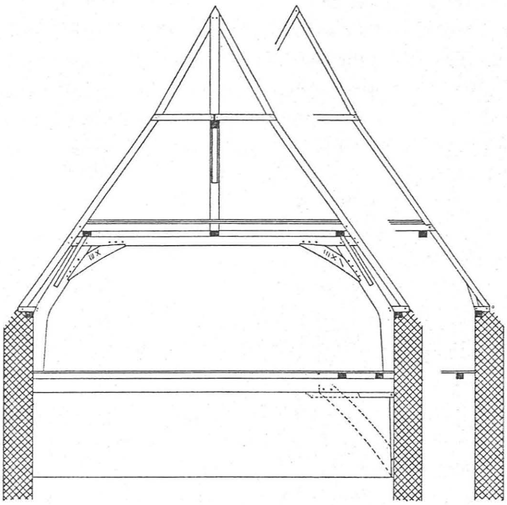

Figure 12
Bergschild 7 in Deventer, 1334 (d). (Drawing G. Berends 1971)

built between 1333 and 1369, Figure 13, and in the carpentry of the choir of the Domkerk in Utrecht with double (stapled) trusses, 1386 (d). This form remained unchanged for a hundred and fifty to two hundred years. Rafters and trusses are separately numbered with broken assembly-numbers on one side. The application of trusses in common rafter roofs (of houses in towns), seems to illustrate the need of firm/stable constructions, in order to comply with the higher requirements set by mediaeval roof tiles in stead of straw.[15] Both flat tiles and the so called over- and under tiles, laid with double overlap in mortar, were very heavy, but subsidised and required by the town government in order to prevent big fires.

First carpenters economised on tie-beams at the foot of roof construction. Later they left out the lower collars and the plate on the middle of the truss. Large ambitious constructions, like those of the Domkerk, have double wallplates and double plates on the lower trusses. During the 15th century next to plates we find purlins introduced into trussed roofs, in the naves of the mendicant order churches in Maastricht around 1395[16] and north of the river Rhine in Utrecht in 1477.

Conclusion

The common rafter roof goes together with the single flooring, both on a distance of 60–90 centimetres.

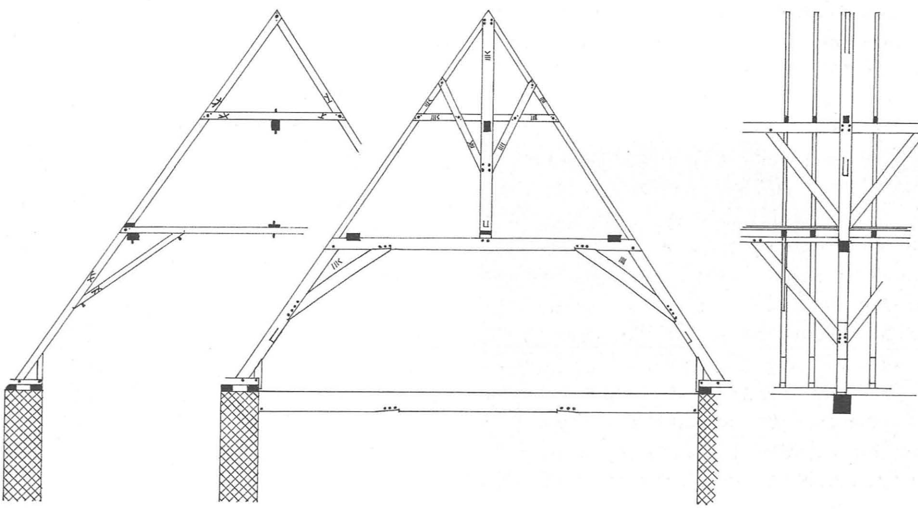

Figure 13
Roof of the nave of the Bethlehemkerk in Zwolle, built between 1333 and 1369. (Drawing by the author 1979)

However, on account of the side walls roof and floor are not directly joined in houses. The walls of these houses are thick, between 60 and 90 centimetres, and sometimes even thicker. The load that the rafters and the beams put on the walls is more or less regularly divided, and the windows are small. This is a Romanesque scheme of building. The Gothic constructional method tends to place great stress upon skeletons made of either stone or timber, applied in all types of buildings (not only churches). Regarding roof constructions, the improvement seems to start with the reduction of long tie-beams. In carpentry, this was achieved when smaller, shorter, square rafters distribute their weight via plates to the trusses which in turn were laid on piers with buttresses and which were often supported by curved braces on the inside. Gothic joisting, comprising sleepers and secondary beams, appears in the Low Countries in the last quarter of the 13th century. In the western part of the south hall of Saint John's hospital in Bruges we find this system in 1285 (d), Figure 14. Sole pieces, curved braces (corbels) and wall pieces (off the floor or on a cantilever) can support the sleepers or binders; this arrangement occurs frequently from the fourteenth century onwards. Curved braces and sole pieces reduce the tension on the sleeper, increasing the stability of the building and in combination with the wall piece, allowing a reduction in the wall thickness. The process of reducing timber in corporation with thinner walls, niches and large windows evoked concentration of forces, both in masonry and carpentry. This constructive change can be linked with traditional styles from Romanesque into Gothic in the way Viollet-le-Duc has explained. Strikingly, in this process carpentry and trusses seem to be earlier than Gothic masonry, at least in Flanders where trussed roofs appear in second quarter of the 13th century.

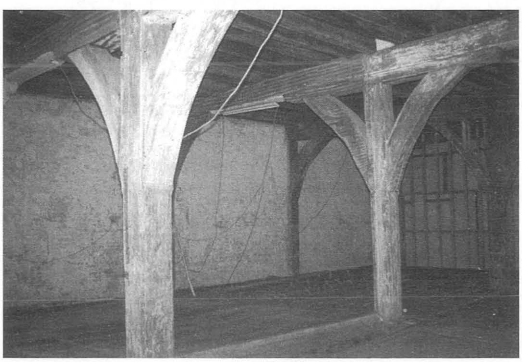

Figure 14
Floor joisting in Saint John's hospital in Bruges, 1285 (d). (Photo by the author 1999)

Notes

1. Harvey 1975, 147.
2. Janse 1989, 147 and 390.
3. Hoffsummer 1995, 76–79.
4. Hoffsummer 1995, 80.
5. Compare with Janse & Devliegher 1963, 323–324.
6. With the help of my collegue Albert Reinstra and the architect B. Delaey.
7. De Vries 2000, 76.
8. Hoffsummer 1995, 88–89.
9. De Vries 2000, 77.
10. Janse & Devliegher 1963, 353.
11. Apart from Gent, all these dendrochronological dates are worked out by RING, Nederlands Centrum voor Dendrochronologie, ROB Amersfoort, the Netherlands.
12. De Vries 1996, 228.
13. De Vries 1996, 230.
14. Janse 1989, 37.
15. De Vries 1994, 81–82.
16. De Vries 1998, 238–239.

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A case of recovery of a medieval vaulting technique in the 19th century: Lassaulx' vaults in the church of Treis

David Wendland

In 1829, the «Journal für die Baukunst», edited in Berlin by Crelle, published an essay with the title «Description of the procedure in the making of light vaults over churches and similar rooms», where, referring to observations made on medieval buildings, a method of building vaults without centering is described.

The author of this essay, Johann Claudius von Lassaulx (1781–1848), was Royal Prussian building inspector at Koblenz (which in that time belonged to the Rhine province within the kingdom of Prussia). As architect he built numerous public buildings in that area, including several large parish churches in medieval style. He was strongly engaged in research, restoration and maintenance of medieval architecture, and a promoter of neo-medieval architecture in his projects and in his writings. In 1846 and 1847 he returned to the subject of vaults in lectures and articles.

The essay in question has been brought to attention by Fitchen (1961, 175ff.). A closer look to Lassaulx' own vault constructions referred to in the essay may offer a more detailed understanding of his vaulting method and give an occasion to discuss the relevance of this publication and its position within the development of building technology in the 19th century.

The building we analyze, the first major project where Lassaulx put in practice his method of vaulting, is the Parish Church St. John at Treis, on the Mosel river, built in 1824–1831.

Contents of the essay

Lassaulx starts his essay declaring that, to his personal conviction, building churches in the medieval styles (gothic and «pre-gothic», i.e. «pointed arch style» as well as «round arch style»), is «not only the most suitable and dignified, but even the cheapest». To build churches in that style is closely linked to vault construction: if ever possible, he says, they should have vaults built of stone. Moreover, «light and wide spanned vaults belong without doubt to the most daring and sensible human inventions», they have high formal qualities, resist to fire and decay. Therefore, Lassaulx says he sought for long for a proper vault construction method. Knowing that at Vienna large domes were being constructed almost completely free-handed, and that in the vicinity flat ovens and fireplaces were built using only some weak rods, he was already for some time trying to imagine how large church vaults could be constructed with similar means.

In literature, there was no indication about how this could be done —«nothing referring to the point in question», apart from the well-known manners of tracing arches, says Lassaulx.

The solution could be found in observations made on medieval vaults. Lassaulx says that he understood the principle of free-handed vaulting by the observations he made on the vaults of St. Laurence's Church at Ahrweiler. Seen from their extrados, these vaults appeared so irregular in their curvature that it

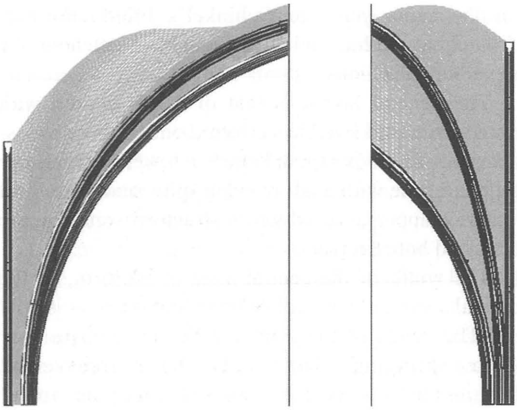

Figure 4
Transversal and longitudinal sections of one bay of the vault in the central nave, as measured (CAD: Ye Zhang)

For the cylindrical columns of the arcade, their details and those of the ribs as well as aspects of the entire layout, the model apparently has been the same church at Ahrweiler where Lassaulx claimed to have understood the art of vaulting.

Analysis of the masonry pattern of the vaults

In 2001, the vaults of this church could be examined more closely, as, before the painting of the intrados was renewed, the courses of their masonry were visible through moisture marks that formed dark lines on the aged plaster.

In some caps, the lines of the bed joints have been measured with a digital tachymeter, as far as they were clearly visible. Along the visible lines, points were tracked with the laser and their three-dimensional position was measured; the resulting point clouds were then examined with a tool for geometric reverse engineering («Surfacer», now called «Ideas freeform modeler») in order to describe their geometrical properties. Apart from the geometry of the ribs and the vault on its whole, information about the masonry pattern of the vault, especially the geometry and the position in space of the courses could be obtained. The measurements and their interpretation regard only the bed joints of the courses on the intrados.

Observing the caps, one can see immediately that the pattern of the courses is far from being uniform throughout the vaults: different caps may present different meshes.

In some caps we can find a regular pattern of courses from the springing line to the top; in many others, though, some sudden changes in the direction of the bed joints are visible —above a certain course the following courses are tilted in a different direction, adjusting with triangular blocks cut *ad hoc*. These discontinuities may occur several times within the same cap. As the vaults were intended to be plastered and their fabric therefore was not expected to remain visible, such irregularities were not disturbing their appearance; for us, however, a closer look to these discontinuities may be interesting, as we may consider them as corrections in the growing

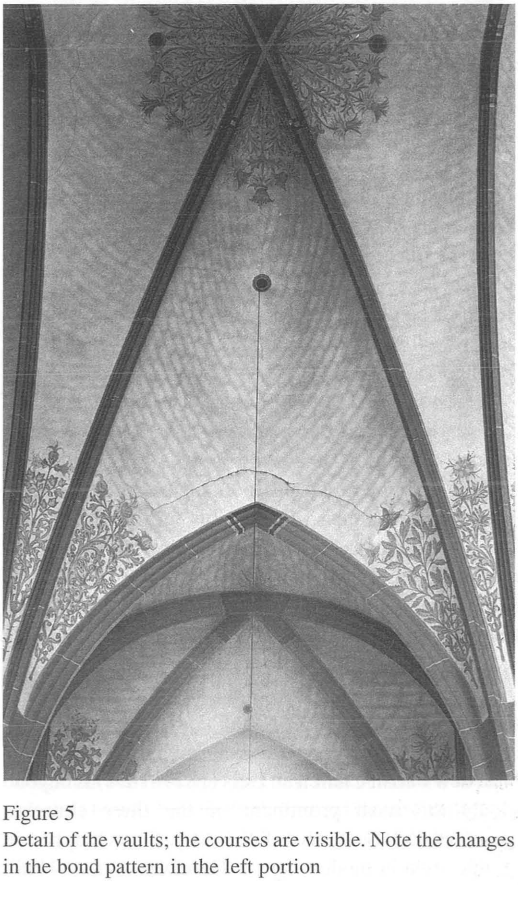

Figure 5
Detail of the vaults; the courses are visible. Note the changes in the bond pattern in the left portion

masonry of the vault; hence, understanding their motivation might lead us to the recognition of some construction principles.

The vaults are strongly domed: all caps present a significant double curvature. Their surface, however, is not spherical. The ridge line in fact is not circular, but describes a characteristic curve with non-uniform curvature (figure 4). This proves that for the construction of these vaults the trammel (rotating pole device) has certainly not been used.

There is no continuity of the masonry bond from one cap to another, but every cap is built independently from the other: behind the ribs, the courses are not continuing, but their fabric is interrupted. This is not visible, but can be deduced by the fact that the bed joints of two neighboring caps are neither continuing in position, nor in direction, nor are they lying in the same or parallel planes. This interruption of the masonry bond between the caps is significantly different from the laying of the courses as it is proposed in the technical literature, especially the dove-tailed pattern (Ungewitter 1859–1864).

The advantage of such discontinuity is that the single caps can be built to a certain extent independently one from the other —in that case, however, some care must be taken to avoid that the growing domed masonry panel would push the centering arches to the sides, causing the collapse of the vault: in fact, Lassaulx writes that in such case the centering arches must be laterally supported. According to the building records, such an accident actually seems to have happened at Treis, after the masons, disobeying to their instructions, had attempted to bring a part of a bay to conclusion (Schwieger 1968, 41).

According to the results of measuring, the curves formed by the visible lines of the bed joints are very proximate to circular arches —in spite of the rather irregular appearance of the cap seen from the extrados. The radii of these circular courses, though, vary from one course to another, and throughout the same caps there are strong differences. Therefore, we can exclude the usage of any kind of sliding template, like the «cherche movible» mentioned by Viollet-le-Duc (1844 ff., and in the «Dictionnaire»).

Further, we observe that the bed joints are approximately lying in planes. These planes are tilted to the inside of the vault; in most cases, they are parallel. This parallelism of the bed joints' planes is

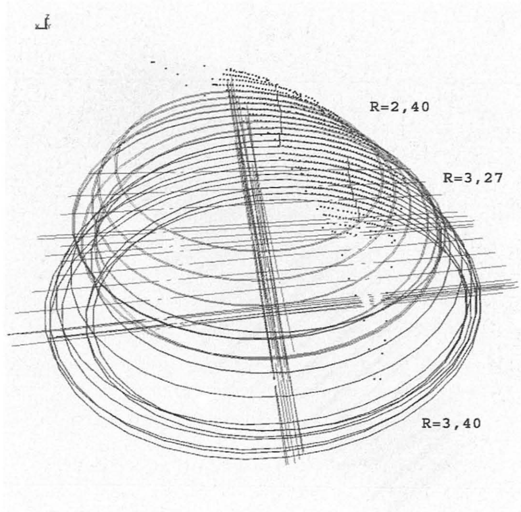

Figure 6
Enclosing circles of the single point clouds, showing the circularity of the bed joints in one portion of the vault (2nd from left in figure 5); the curvature is varying throughout the vault.

surprising if one considers that in the technical literature throughout the second half of 19th century —namely Ungewitter and the manuals based on him— the plains containing the bed joints are described as being radial, all passing through the center of curvature of the vault.

At Treis, these planes are parallel, less or more tilted to the inside; only at the discontinuities mentioned above, their direction sometimes changes drastically. However, in masonry with curved bed joints it is reasonable (and automatic) that the planes are parallel. Otherwise, in case they formed an angle, the thickness of the joint would not be uniform, but would vary according to the local distance from the axis (e.g. the center of curvature in case the planes would be radial); such a variation in the thickness of the joint would be questionable not only in regard to the working process and the stability of the masonry fabric, but would also cause problems to the geometrical control of the rising structure. Therefore, the radial disposition of the pattern as proposed by Ungewitter and others appears more difficult and less practical.

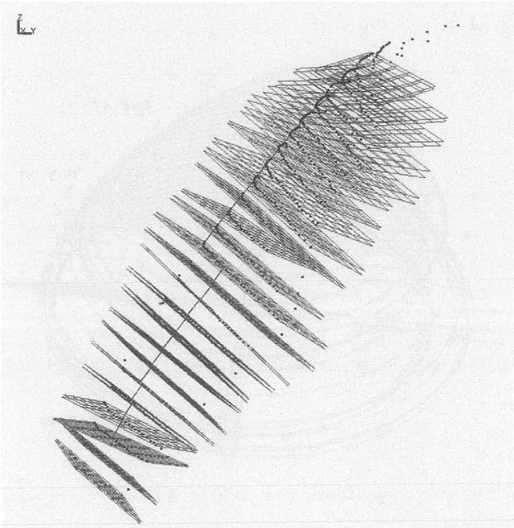

Figure 7
Enclosing planes of the single point clouds, showing the parallel planes of the bed joints in figure 6

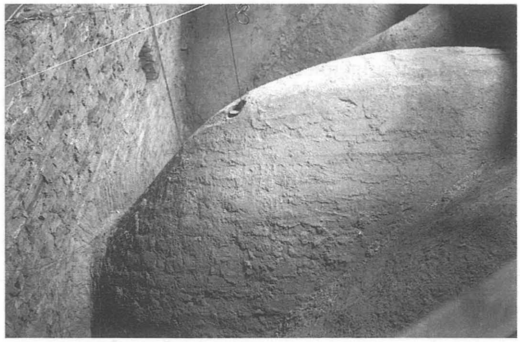

Figure 8
Extrados of the vault. The «horizontal» courses are visible, as also the form of the slope of the vault

As already mentioned, by diagonally tilting the planes of the courses, like in the dovetail pattern, in most cases it is easier to obtain curved (and therefore self-supporting) courses. In cylindrical caps, such tilted courses will be curved without giving a double curvature to the cap.

Building the vaults at Treis, Lassaulx renounced to this possibility —as mentioned, he gave a strong double curvature to the caps and apparently endeavored courses that begin and end approximately in the same height above the springing line. In some cases the courses seem to have resulted tilting towards the diagonal ribs perhaps because these are longer than the longitudinal and transverse ribs, and were then corrected, continuing with courses running parallel to the springing line. Some of the large caps in transversal direction to the nave have courses that are slightly tilted towards the longitudinal ribs, contrary to the scheme of the dovetail pattern.

In most cases, however, especially in the higher portions of the caps, the bed joints begin and end in about the same height above the springing, but their planes are tilted to the inside, so that in prospect the bed joints appear as curves.

In the summit, the courses of the neighboring caps meet each other and are bound together in a herringbone manner. There is no re-entrant groin; except for a small portion at the vicinity of the longitudinal or transverse ribs, the surface of the vault at the ridge is continuously curved.

At the locations where we observe the corrections of the masonry pattern, the changes to the inclination of the bed joints' planes appear to be of minor importance and altogether not systematic: in some cases the planes change direction, in some cases the inclination increases significantly. Hence, these corrections probably were not aimed to reduce the inclination of the beds.

The major alterations in these corrections regard the curvature of the courses, and they are definitely systematical. In those caps that have been measured and that present these corrections, the radii of curvature of the courses are drastically reduced above the locations where their direction changes. In some cases, even such corrections that are hardly visible to the eye lead to a considerable reduction of the radius of curvature. Therefore, Lassaulx' effort seems to have been oriented to organize the courses in such manner that, without affecting the geometry of the vault, their radius of curvature would be as small as possible. This is very consequent, as the basic principle of free-handed vaulting, according to what Lassaulx is writing, depends on the arch-like curvature of the courses.

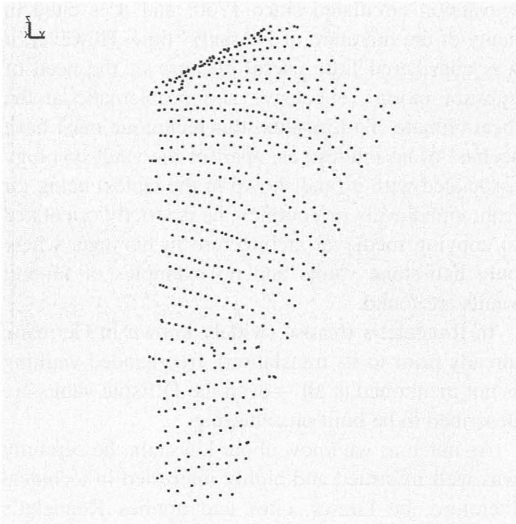

Figure 9
The courses of the left cap, Figure 5, as point clouds, in prospect

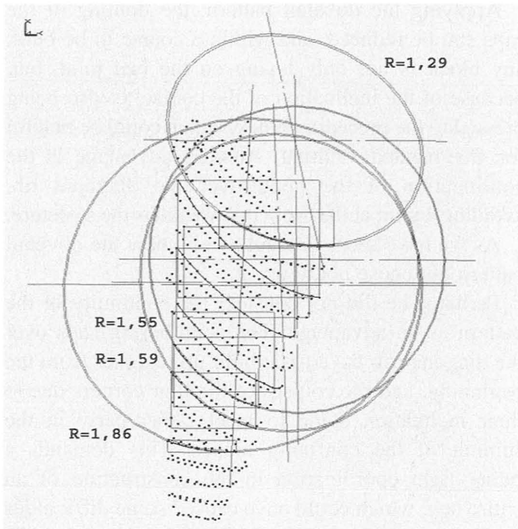

Figure 11
The bed joints' curvatures of the same portion, showing considerable reductions of curvature after the corrections in the bond pattern

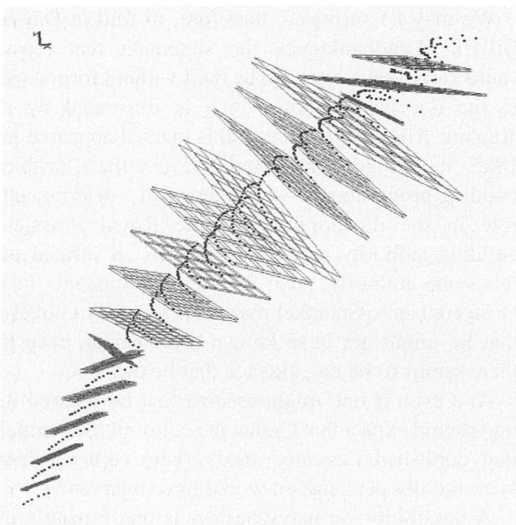

Figure 10
The bed joints' planes of the same portion

The general strategy, as emerges from these observations, seems to have been to rise the caps in their lower part (starting from the corbelling spandrel) along the ribs, gradually inclining them towards the inside, but then, in the upper half, to proceed straight ahead, giving a uniform inclination to the cap over a greater portion. The resulting form of this portion is that of an upright cylinder inclined towards the inside of the vault —the courses are thus bowing more and more to the outside of the ribs, and their arches are closed to 1/3 circle or more. Only at the summit the direction changes, where the courses are meeting those of the neighboring cap and therefore become shorter: the inclination of the vault's surface strongly decreases and the vault is closed; in this area, the bond becomes rather irregular, and the bed joints neither form circular arches nor planes.

Lassaulx' choice of the vaulting pattern

Within the examples of medieval vaults in Lassaulx' proximate sphere of action (Rhineland, northern Germany, the Netherlands) either dove-tail patterns may be encountered, as also patterns with courses running parallel to the springing line. In the last, at the summit of the domed caps the bed joints form a characteristic lens-like figure.

Applying the dovetail pattern, the doming of the caps can be reduced, and within a course to be built, any block is not only laying on the bed joint, but, because of the inclination of the course, is also being pressed to the preceding block, which could be helpful for free-handed vaulting. Another advantage is the continuation of the bond over the diagonal rib, avoiding a joint at the groin that weakens the structure.

As we have seen, Lassaulx well knew the dovetail pattern but chose not to use it.

Perhaps, he did not consider the continuity of the pattern as an advantage: The neighboring caps over the diagonal rib have to be built up together from the beginning, and the courses of the four corners due to their inclination come to meet rather early in the summit of the confining arches. This demands a rather tight coordination in the construction of an entire bay, which could have caused some difficulties to the building process especially in vaults with greater dimensions.

Another reason might arise from his opinion of how the bond pattern of a vault influences on the distribution of the loads and the resulting thrust —as it is quite obvious from the regarding passage of the essay, Lassaulx probably believed that a vault with horizontal courses would produce less horizontal thrust than if built in the dovetail pattern.

Another type of bond pattern that Lassaulx probably knew has its courses only slightly tilted towards the center, as described as typical for English vaults by Willis (1842, 8), and that present an intermediate solution to those mentioned. The drawing given by Lassaulx of a vault with tilted courses is much more similar to this typology, that to the current dovetail pattern.

THE LACK OF TECHNICAL INFORMATION

In his essay, Lassaulx states that neither he could find masons capable to build vaults without centering, nor was there any information available in literature. As to the first statement, obviously today it will be hardly possible to verify within what geographical range this might have been true. The second, though, can be interpreted on the basis of a comparative study of the technical literature available to him.

D'Espie's book describing timbrel vaulting, for instance, was well-known in Germany; a German translation circulated since 1760, and it is cited in many of the literature of Lassaulx' time. However, it was considered little useful because of the need of gypsum mortar, expensive and problematic at the local climate. To Lassaulx, this technique must have seemed of no interest, as, apart of the vault typology associated with it (and shown in the tables) being far from «medieval» or «gothic», he is strictly orientated to copying medieval architecture in his area, where only half-stone vaults and no examples of timbrel vaults are found.

In Rondelet's treatise (widely known in Germany already prior to its translation), free-handed vaulting is not mentioned at all —even the D'Espie vaults are described to be built on centering.

As much as we know about Lassaulx, he certainly was well informed and highly interested in technical literature; he knows, cites and applies Rondelet's treatise, and we have to imagine him as a bibliophile person. In his publications, he habitually gives extensive reference to the sources he used. Hence, we should consider seriously his statement on the lack of written instructions on free-handed vaulting.

We may be surprised, therefore, to find in David Gilly's «Landbaukunst» the statement that cross vaults (and only those) can be built without formwork in the dovetail pattern, which is illustrated by a drawing. The third edition of this manual appeared in 1805, it was generally used and circulated within building professionals —its author had a determinant role in the development of the Royal Prussian building authority, and Lassaulx was an official of this same authority. Also the fact that Lassaulx had close contact to Schinkel makes it extremely unlikely that he might not have known this manual, even if there seems to be no evidence that he did.

And even if one might assume that he ignored it, one should expect that Crelle, the editor of the Journal that published Lassaulx' essay (who certainly had known Gilly personally), would have intervened.

A possibility we may consider is that Lassaulx in fact knew this manual, but does not mention it, because he might not have found useful the information given in it, but would not be in position to refer to it in a critical manner. As a matter of fact, Gilly only writes that «skilled masons» are needed to build a cross-vault without formwork, without giving any precise description of the procedure. In the drawing, the masonry pattern is represented only in

the central part of the vault, where the bed joints form a square turned 45° respect to the plan; the lower courses, as they depart from the springing, are not shown —neither in the plan, where they would appear curved, nor in the section. Gilly does not offer any precise description of the masonry pattern in drawing or in text, and therefore would not offer sufficient information to build vaults like the one in Treis.

What Lassaulx found lacking, and what he contributed to the technical literature, is in fact a precise technical description of a construction principle that allows its reproduction. In his essay, avoiding any consideration about the geometry of vaults (he would dedicate his lecture published in 1846 on that topic) he describes in a very concrete and clear manner the principle, and formulates guidelines of this type of construction. Such an instruction gives the architect the possibility to interfere in the construction process, and to link construction and architectural design.

THE POSITION OF LASSAULX' ESSAY IN THE TECHNICAL LITERATURE

As far as can be said today, Lassaulx' essay met a rather broad attention. Beyond the distribution of the «Journal», translations of the essay were published in England and France. In England, it appeared in 1831 in the «Journal of the Royal Institute» (Schwieger 1986; Fitchen 1961), reported by Whewill (who had added a text by Lassaulx to his «Architectural notes on German churches» in 1842); this translation was cited by Willis (1842).

In France, it was published in 1833 in the «Journal du Génie Civil» (Schwieger 1986).

Apparently, its contents have also found their way into the technical literature. In Wolfram's exhaustive «Complete Manual of the Entire Building Art» (1838) that is mainly depending on Gilly and Rondelet, the essay is cited and referred to. In the chapter about the building of the caps (vol.III.2, p.85), the principle of arched, self-supporting courses is explicitly pointed out (with reference to Lassaulx), and the drawings illustrating that chapter (fig.198a+b) are clearly depending on those of his essay (fig.5+6). In order to obtain the necessary curvature of the courses, the dovetail pattern is recommended.

Where Viollet-le-Duc explains the building of groin vaults in his essay on construction, published in several parts in the first numbers of the «Annales Archéologiques» (1844 ff.), apart from the use of a sliding template he mentions exactly the same principles as Lassaulx: « . . . chaque rang de meollons étant bandé, et formant un arc de l'arête diagonale au formeret, ou à l'arc-doubleau, pouvait être abandonné à lui-même sitôt que le dernier morceau était pose». (2.1845, p. 148). He mentions Lassaulx only in 1847; from 1846, however, in the «Annales» great attention is given to Lassaulx by Didron and other authors, and there is evidence for close contact. We can state that the French translation of Lassaulx' essay had been published 1833, twelve years before, and that he had come to the attention of the readers of the «Bulletin Monumental» just a few years before (Lassaulx 1838; in the following number, he was mentioned as coeditor), and therefore we find it interesting to suppose but cannot prove that Viollet-le-Duc's statement is depending from him.

Breymann (1849) —probably the most successful manual in Germany, published and republished in 7 editions, with two revisions, up to 1903— doesn't mention the essay. We only find a reference to Lassaulx' later essay from 1846, where a summary of the 1829 essay is given in a long footnote. But he cites (and mentions) Wolfram, so it is certain that he knew the contents of Lassaulx' essay. Besides, Breymann also extensively cites Willis' article on the geometric construction of vaults (1842) —without mentioning its author— where he could find a reference to Lassaulx' essay (this also proves that Breymann is very selective in mentioning his sources). In fact, we can find a drawing showing the auxiliary devices mentioned by Lassaulx, the trammel and the hanging stone device (t.24, fig.1). As both are shown together, it is hardly believable that the source may be other than Lassaulx.

The principle of self-supporting courses is only implicitly mentioned, the text on (free-handed) building of the caps (p.68) is based mainly on Gilly —anyway, it is essential that it appears at all. For the rest, Breymann gives a much more detailed graphical representation of the cross-vault built in dovetail pattern than Gilly: in the plan, all courses are drawn, and their projection in the lower parts is carefully traced.

Its reproduction, therefore, is easier than following Gilly. A representation of the courses in elevation,

however, can be found only in the 4th edition revised by H. Lang, in 1868.

Ungewitter —his manual on gothic architecture appeared in several deliveries from1859 to1864, a revised and extended edition was published by Mohrmann in 1890— doesn't mention Lassaulx. In the foreword, however, he mentions two building manuals: Gilly and Wolfram. As stated above, the lecture of Wolfram's manual gives knowledge of the contents of Lassaulx' essay, without needing to recur to this source directly.

Here, a detailed and exact description of the geometrical disposition of the courses is offered in the text and the illustrations, describing the overall geometry of the severy, the position of the bed joint planes, and the curves of the courses themselves, referring to the principle of self-supporting courses. In difference to Lassaulx, the dovetail pattern is preferred (as already in Wolfram).

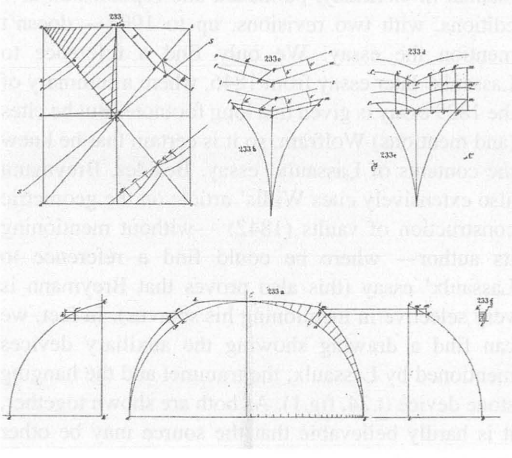

Figure 12
Ungewitter 1859–1864, t.8 (details). Tracing of the courses of a groin vault with dovetail pattern

Such a precise description (leaving apart the question of its correctness) enables the architect to design all details of the vault, in general of a gothic construction, and gain complete control of the working process. The close link between the properties of materials and their working to the design and the appearance of the entire building, as it had been clamed already by the neo-gothic avant-garde of the early 19th century and aimed to namely by Lassaulx, finally becomes possible.

Acknowledgements

The present study is part of the author's doctor thesis in preparation on free-handed vaulting techniques that is supervised by Prof. Dr. Kimpel, University of Stuttgart. The author shares with Lassaulx the passion of vaulting, which he developed since as a student he had occasion to collaborate in the planning and realization of vault reconstructions, and his studies on the work of Alessandro Antonelli since 1992. Thanks to Pastor Rodermann at Treis, and to María José Ventas Sierra for the photographs and her collaboration.

Notes

1. The German translation of the 6th edition appeared only in 1836.
2. This is not the same edition David Gilly used and gave to the knowledge of the German public.

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Design-build and building efficiency in the early twentieth century United States

Alfred Willis

The history of construction management as it evolved over the twentieth century in the United States remains largely unwritten. Instead, contributions to American construction history have concentrated on the organization of skilled and unskilled building labor, the evolution of concrete and certain other building technologies, and on the development of the architectural profession as such. By describing the extent and place of design-build activity in the early twentieth-century American building world, this paper suggests the rich possibilities of a new area of research for historians of both architecture and construction, as well as of business in general.

Design-build is a mode of building procurement combining the tasks of designing and building an edifice under a single responsibility, thus allowing a close integration of the properly architectural and properly constructive work. Thus defined, design-build may seem as old as architectural construction itself, and to hark back to the building cultures of ancient Egypt or Greece. More specifically, however, and as used in this paper, «design-build» refers to a «building delivery method that gives the owner both design and construction services under a single contract» (Wright 1988, 59). It is one of the characteristically twentieth-century ways of organizing the construction enterprise, «a method of project delivery in which a single entity provides to the client all of the services necessary to both design and construct all or a portion of the project» (Twomey 1989, 3).

Design-build has been and continues to be practiced in a more or less similar form in many countries around the world. Its variants include the «bridging method», «novation design and building, «the «package deal», and the «turnkey method» (Sebastyén 1988, 259). The activity of the firm of Perret *frères* (Auguste and Gustave Perret) in Paris provides an especially well known example (Britton 2001, esp. 20, 22). Japan's Takenata Corporation, now a major player in the design-build sector, traces its history as a design-build company back to the seventeenth-century (http://www.takenaka.co.jp/takenaka_e/his/history.htm). Despite both its apparent roots in traditional craft-building and its actual roots in early twentieth-century construction-management practices, (western) design-build is usually considered to be a mid-twentieth-century novelty. This allegedly «new procurement method» (Sebastyén 1988, 259; *cf.* Solomon 1991) is perceived as having been introduced into the United States around 1970 as a challenge to the then dominant mode of divided-responsibility procurement. The notion persists because practically all available studies of building production in the twentieth-century United States (mostly written by architectural or art historians) attribute a normative status to the latter system, which since the late 1800s has been clearly preferred by American architects. These studies consequently marginalize both the products and the proponents of the alternative, single-responsibility system (*cf.* Davis 1999, 126, 336 n. 5).

To begin to correct the imbalance evident in the historiography, the first section of this paper describes some of the numerous design-build firms —both large and small— operated successfully throughout the United States in the first half of the twentieth century. The primary empirical evidence for what is reported here has been drawn from commercial ephemera, city directories, trade magazines, and general-interest periodicals. Considerable secondary evidence has been harvested from the World Wide Web.

Some American Design-Build Companies

Amy Slaton has mentioned some of these firms in her ground-breaking monograph on *Reinforced Concrete and the Modernization of American Building, 1900–1930.* One «functionally integrated engineering/building firm», the Boston-based Aberthaw Construction Company, she considers as a case study (Slaton 2001, 157–166). Slaton calls attention to the competitive advantage enjoyed in the early twentieth-century American market for new industrial buildings by such «firms that included an engineering division able to design factory buildings and a construction division able to erect the buildings from start to finish» (Slaton 2001, 139–140). Quoting an opinion from William Haber's 1930 study of *Industrial Relations in the Building Industry*, she views the design-build firm as especially well positioned to innovate in the construction field of the early 1900s (Slaton 2001, 140). While this view appears to be well founded, Slaton's focus on factories does leave one with an inadequate appreciation of the application of design-build methods to the production of the full range of American building types.

Among the further examples of combined engineering and building firms Slaton cites is Lockwood Greene Engineers, Inc. This company, which remains in business, traces its history to 1832 (Lincoln 1960) and thus can characterize itself as «America's oldest professional services firm in continuous operation for industrial engineering and construction» (http://www.lg.com/about/lg-story.asp). Although the firm has come to specialize in industrial process engineering and related construction, in the early to mid-twentieth century Lockwood Greene did a large business in design-build work of an architectural character. A 1929 publicity booklet included a selected list of clients for such work running to twenty-three names representing fourteen cities, together with illustrations of numerous school, office, commercial, and religious structures (Lockwood Greene Engineers, Inc. 1929).

The Austin Company, incorporated in 1904 in Cleveland, Ohio as the Samuel Austin & Son Company, is another important design-build firm that evolved into a nationwide concern and remains in business today (http://www.theaustin.com). But whereas the origins of Lockwood Greene were in the engineering and construction of large mill buildings, The Austin Company produced architectural, as well as industrial, work from the outset (Greif 1978, 25–53). Although by the late 1910s the company was becoming best known for its prefabricated «Standard Factory Buildings» of various sizes (and combinable into a theoretically endless number of configurations), it continued to design and build architectural work of high quality for a variety of non-industrial purposes (Greif 1978, 54–92). Throughout its history the company's governing principle has been of «undivided responsibility» for both design and construction of buildings for its clients (Greif 1978, 34–35).

Early on, The Austin Company found itself facing a number of local (not to mention regional or national) competitors in the niche market for factory buildings erected quickly under a design-build contract. For instance, the Truscon Steel Company, operating out of Youngstown, Ohio, from the early 1900s to the early 1960s (http://www.royness.com/product_2.html), produced prefabricated steel building modules. These modules could be combined in various ways in accordance with clients' needs as presented to the company's design advisors (*cf.* Truscon Steeel Company 1919). Similarly, Cleveland's Crowell-Lundoff-Little Company offered clients «eleven styles of economy factory buildings fully designed and ready to build,» as well as the building services themselves.[1] In the mid-1920s the Cleveland-based H. K. Ferguson Company, «engineers and builders» offered nine types of standard factory structures, as well as custom design services on either a design-build or design-only basis (H. K. Ferguson Company 1925).

Other competitors, while emphasizing industrial construction, diversified like The Austin Company into

other building types as well. A notable example was the William Steele & Sons Company of Philadelphia. Billed as «Engineers, Constructors» and prominently illustrating factories and warehouses in their advertisements,[2] this firm is perhaps best remembered for producing Philadelphia's historic Shibe Park baseball stadium (erected 1909; demolished 1976) (http://www.ballparks.com/baseball/american/shibep.htm).

In all probability, a large number of early twentieth-century American design-build firms either concentrated on properly architectural work or eschewed industrial construction altogether. Several of them specialized in bank buildings. A. Moorman and Company, which carried on business in St. Paul, Minnesota, from the early 1900s through the late 1970s (http://special.lib.umn.edu/findaid/html/mss/nwaa0075.html), was responsible for numerous smaller bank buildings throughout the American Midwest (*e.g.*, Bank Buildings of Dignified Aspect 1921). Stylistically, their products seem to have been conservative. Although the significance of the firm to architectural history most likely lies in its bringing high-style classicism to many nondescript small towns, it has (rather unfortunately) been remembered by posterity for its involvement in an unsympathetic remodeling in the mid-1950s of Louis Sullivan's bank at Owatonna, Minnesota (Millett 1985, 159–168).

Like the A. Moorman Company, Hoggson Brothers got its start through the decorating business before specializing in banks and then diversifying. Noble Foster Hoggson established himself as a decorating contractor in New York City about 1889; William J. Hoggson joined the company some six years later. By the 1910s the firm's work included small- and large-scale bank buildings, public libraries, houses, churches, hotels, and multistory office towers. Many of them were illustrated in a unique, lavishly produced promotional periodical, *The Hoggson Magazine*. By 1914 Hoggson Brothers had projects under construction across literally the whole height and breadth of the United States.[3] The company's reputation could have been done no good by the involvement of William Hoggson in a financial scandal in 1927–28 (Trial of Big Suit Over Hotel Begins 8 November 1927; Accountants to Tell How Millions Went 20 November 1927; Accountant Tells How Millions Fled 1 December 1927; $525,477 Awarded to Hotel Investors 2 August 1928). Nevertheless, Noble Hoggson remained a prominent figure in American building business and the company received enviable commissions until at least 1930 (Noble F. Hoggson of Building Firm 26 October 1939).

The Bank Building & Equipment Corporation of America may have taken up the market niche vacated by the decline of Hoggson Brothers in the 1930s. Founded some time before 1940, by the 1960s it had diversified into the hospitality sector and by the 1970s into the healthcare-facilities field.[4]

Beezer Brothers of Seattle (active 1907–1923) offered integrated design and building services to clients widely scattered along the Pacific coast of the United States (including Alaska). Their quick success has been attributed to the company's management practices. As their practice grew, they focused increasingly on banks and religious structures (Rash 1994, 144–149).

The Walter Butler Company, with offices in St. Paul and Detroit, Michigan, and active in the 1940s, appears to have served a nationwide clientele consisting largely of religious organizations. For these organizations the firm offered «complete architectural, engineering, general contracting, and financing services»[5] to produce schools, hospitals, convents, churches, and other buildings in a variety of both traditional and Modern styles.[6]

The Cincinnati, Ohio-based Ferro-Concrete Construction Company variously built works designed by independent architects or engineers (as in the case of the Parr & Fee's 1907–09 Europe Hotel, Vancouver, British Columbia, Canada) (http://www.stgeorges.bc.ca/marker/main/europehotel/fullreport.htm). It also served as design subcontractors to independent architects (as in the case of the 1902 Ingalls Building in Cincinnati) (http://enr.construction.com/aboutUs/125enrHistory/990201.asp). Additionally, it would offer design-build services directly to project owners (as in the case of the Finch Building, Aberdeen, Washington) (http://www.e-history.com/Site/Site_USA_WA_G.htm).

In contrast to the above firms operating on a national (even international) —or at least regional— scale, the Los Angeles firm of Meyer & Holler concentrated on a local market. Incorporated in 1906, Meyer & Holler developed into one of the largest building firms in Los Angeles before declaring

bankruptcy in 1932 as an indirect result of litigation related to California's architectural registration laws. Apparently founded as a design-build concern, the company at any rate opted definitively for the design-build approach very early in its history. At first emphasizing domestic work of an increasingly important scale, Meyer & Holler switched to an emphasis on commercial work after World War I. Integral to the company's strategy for success was the offering of architectural design services of an unusually high level of quality, which it was able to due as a result of hiring some of the finest architectural design talent available in southern California in the 1910s and 1920s. Only on very rare occasions did it contract to erect projects designed by independent architects (Willis 2000).

Alongside the large firms just described, numerous smaller design-build firms operated in the major and minor cities across America during the first half of the twentieth century. Not surprisingly, many of them reached the peak of their success during the booming 1920s. In most cases, little is known about them beyond the fact of their pursuit of design-build contracting.

Federici Armezzani & Co. were design-builders operating out of Paterseon, New Jersey, in the very early twentieth century, and as such were responsible for the remarkable reinforced-concrete church of Our Lady of Loretto in Brooklyn, New York (Concrete Church with Ornamental Cast Concrete Details 1928). Hans Baer has been recorded as a «designer and builder» active in Newark, New Jersey, in the mid-1920s (When a Builder Builds 1924). Arthur H. Higgins was reportedly an «architect and builder» around the same time in Staten Island, New York (Two Types of Popular House Designs 1924). The Fred F. French Company of New York City, best known as a developer, kept architects on staff and engaged at least occasionally in design-build work (*e. g.*, Two Modern Apartments for City and Country 1918). In Jacksonville, Florida, Henry A. Taylor operated primarily as a builder but sometimes provided architectural services as well to his clients (http://jaxhistory.com/architects.htm). Thomas K. Windham, Inc. of Atlanta, Georgia, promised clients a service that «is complete, from the assembling of the plans to the planting of the shrubbery» (Fistere 1930, 45). The H. E. Hanna Company of Tulsa, Oklahoma, was reported in 1925 to have comprised «seven complete departments — the retail lumber department, the architectural department, the construction department, the decorative department, the electrical department, the planing mill, and the financial department.» This organization clearly indicated a core business devoted to design-build (Handley 1925). On his letterhead of 1932, H. K. Nicewanner of Muncie, Indiana, portrayed himself as a «designer and builder» of houses, factories, and storefronts (Builders Active in Modernizing Drives 1932). The unusually successful John W. Murphey Building Company, designed as well as built numerous residences in and around Tucson, Arizona (Keith 1931, esp. 66–67).

In southern California, an enormous number of smaller operated in the early twentieth century, no doubt providing stiff competition for Meyer & Holler and The Austin Company (*e.g.*, Three Plants to Build 18 November 1923). Here only a tiny fraction can be mentioned. One of the most successful, the Frank Meline Company specialized in houses for the relatively well-to-do, such as the remarkable home of silent-film star Tully Marshall (A Moroccan House in California 1923.). A number of companies specialized in designing and building the more modest bungalows for which southern California became famous: among them, for example, were Pacific Home Builders (*e.g.*, Blending of Chalet and Bungalow 1914) and the Edw[ard] E. Sweet Designing and Building Company. Around 1910–11 this firm became one of the many in California that published so-called «bungalow books» to promote their business (Edw. E. Sweet Designing and Building Co. [1911?]). The brothers Arthur S. and Alfred Heineman are best known for designing and building bungalows, but their extensive record of design-build work in fact covered a range of building types (Winter 1997). John Manley Close specialized in designing and building apartment houses, noted for their exotic styling and mostly built on speculation. «We design —we build— we finance,» stated one of his advertisements in 1924.[7] Franklin Harper was a design-builder remembered for his striking Granada Shops and Studios building (Gleye 1981, 82; Moore, Becker and Campbell 1984, 146–147). Indicative of the proliferation of design-build firms in Los Angeles during the boom years of the 1920s were illustrations of work by three different firms —The Austin Company, the Garden City Company of California,

and Luther T. Mayo, Building Contractor— in a single 1922 issue of the *Los Angeles Times*.[8]

DESIGN-BUILD AS A PHENOMENON IN AMERICAN BUILDING HISTORY

From the foregoing brief, and necessarily very incomplete, survey, it is obvious that the single-responsibility, design-build procurement system enjoyed a widespread popularity from 1900 onward throughout the United States. Although never the only system in use and probably never even the dominant system, single-responsibility design-build procurement remained viable well beyond the end of World War II. Evidence is found in publications,[9] in expressions of concern about the system by independent architects committed to the divided responsibility contracting (Banister 1954, 27), and of course the survival of such firms as The Austin Company. Both large and small firms were involved. Their products ranged widely in scale and quality, but included many structures meeting extremely high standards of design and structural integrity.

Those firms emerged and flourished in the United States during a time of great (though unsteady) growth in the American construction sector. From the late 1800s into the 1920s, new managerial challenges emerged as contractors adapted their organizations and craftsmen their ways of working to the demands of increasing volume and scale of building in burgeoning urban areas. By necessity those involved in the building trades sought new approaches to meeting those challenges (Clark 1928, 182–223).

One leading such approach, «scientific management,» addressed the challenges of increasing the efficiency with which the actual work of building was carried on. Both of the major proponents and theoreticians of scientific management, Frederick Taylor and Frank Gilbreth, originally applied their seminal work in modern management theory to construction problems. Taylor, though by training a mechanical engineer, worked from 1896 with Sanford E. Thompson on motion studies in the building trades; they co-published two treatises on concrete construction in 1905 and 1912 (Copley [1923] 1993, 1: 411–413). Gilbreth was a general contractor (Gilbreth [1925] 1973, 19–23) whose practical experiences in managing construction work he set forth in his highly influential *Field System* published in 1908 (Gilbreth 1908 [1973]). The influence of Taylor and Gilbreth is clearly evident in Daniel J. Hauer's treatise on *Modern Management Applied to Construction* of 1918. Martin Greif has speculated on the influence of Taylor's theories on the practices of The Austin Company (Greif 1978, 18). Slaton has documented a more direct impact of Taylor and Thompson on those of the Aberthaw organization, which she characterizes as «typical of those of large firms of its day» (Slaton 2001, 158). But the contributions of Taylor and Gilbreth to the development of construction management specifically seldom receive more than a passing mention in the general historical literature (*cf.* Sebastyén 1988, 242; Davis 1999, 134). The pervasion of early twentieth-century American construction scientific management remains to be documented, in part from evidence that can be collected from the periodical literature of the period (*e. g.*, Moulton 1930).

Besides scientific management itself, other approaches addressed the challenge of increasing the efficiency of the contracting enterprise itself, broadly defined as the procurement of new buildings through the contractually governed cooperation of owners, architects, engineers, contractors, and building workers. The best known (and most permanent) of this class of approaches involved the displacement of procurement by individual contracts by general contracting in the context of a divided-responsibility arrangement wherein an architect positioned himself as an intermediary between a client and the builder (Delhi 1908). Another, intending to reduce costs and delays in construction while giving builders an incentive to keep quality high, was the exploration of various forms of unit-price and cost-plus contracts (Affelder 1924; Tuttle 1931). Exploitation of single-responsibility contracting was a third such approach, intended to reduce inefficiencies perceived as arising in the construction process due to conflicts of interest, or inadequate cooperation, between architects and builders (Bowen 1913).

If the evidence for the existence of single-responsibility, design-build contractors in early twentieth-century America is fairly abundant, the evidence for exactly how they operated is relatively scant. Much of the surviving evidence is provided by the firms' own advertising brochures and published

displays. Combining text, pictures, and diagrams, these advertisements emphasized the efficiency or economy of a design-build approach, while positing its novelty (and, by implication, modernity).

Advertising graphics used by The Austin Company in the 1920s contrasted the simplicity of its «unit responsibility» approach to the complexity inherent in «the old way» of contracting, which exposed the client to the pitfalls of dealing separately with an architect and (potentially) numerous contractors (Austin Company 1925, 42–43; *cf.* Greif 1978, p. 65). As the company had done since at least 1913 (and perhaps as early as 1901), it referred to its «new way» of doing business as «The Austin Method» (Greif 1978, 35). Meanwhile, in a long series of advertisements, The Austin Company had intimately associated its «Austin Method» with low-cost and speedy construction.[10] The overall effect of these coordinated efforts at self-representation was to associate single-responsibility contracting with overall efficiency in the minds of potential clients.

Hoggson Brothers, which promoted their single-responsibility approach to contracting as the «Hoggson Method,» used two telling graphics in some of the firm's earliest national advertising.[11] The first was a diagram purporting to show Hoggson Brothers' organization as a firm «whose business it is to select and supervise every phase of bank building and residence work, from the original plans to the smallest detail of the furnishing and decoration.» In this diagram, «Hoggson Brothers» itself appears at the center of an array of all the tasks to be carried out in a building project, and thus in a position to control all of them simultaneously.[12] The second diagram again has Hoggson Brothers in a central position, but now shown between the Owner and a triumvirate of key personnel within the Hoggson Brothers organization —the architect, the decorator, and the builder— all under the control of the firm's administration. In a 1916 article in the *Hoggson Magazine*, Hoggson Brothers showed through a series of captioned illustrations how a slight variant of that second diagram related to the actual internal organization of the firm. The same article explicitly noted the two main features of the «economical, efficient, and equitable» single-responsibility approach touted as the «Hoggson Building Method» —combining «the functions of the architect and engineer, builder, and decorator, in one comprehensive organization, under a single management,» and guaranteeing «in advance to the prospective building owner the cost of his operation» (Profession of a Business Firm 1916).

It seems likely —even certain— that design-build under single-responsibility contracts resulted in the delivery of numerous efficiently and economically constructed buildings to countless satisfied owners across the United States during the first half of the twentieth century. These buildings, by the way, probably satisfied the aesthetic as well as the financial and practical needs of those owners. While many of these buildings were conservative or even pedestrian in design —and many more were frankly utilitarian— others were no doubt striking or even innovative (Willis 200, 601–602).

It seems unlikely that this form of procurement survived from nineteenth-century craft-based master-building, or that it evolved out of that tradition in any simple way. Although leaders of early twentieth-century American design-build firms (like Samuel Austin of the Austin Company) did have experience in the building trades, many others came to design-build contracting from quite alien backgrounds. For example, Noble Hoggson of Hoggson Brothers had an academic background as a graduate of Yale University; William Hoggson brought to the same firm experience in manufacturing (Profession of a Business Firm 1916, 41, 43–44). Mendel Meyer of Meyer & Holler came to contracting from a varied background in retailing, food processing, and stabling.[13] John W. Murphey of Tucson held a university degree in engineering (Keith 931, 68). Rather, single-responsibility design-build procurement more likely developed, alongside the divided-responsibility system and general contracting, out of the particular relations of building production prevailing in America shortly before and after 1900. Its promises of efficiency, simple and square dealing with clients, and fair profits to the contracting firm, responded to contradictions inherent in a building world founded upon the exploitation of wage labor on the one hand and (through the competitive bidding system) the exploitation of owners' instinctive thrift on the other. In this world, the competing interests of contractor, architect, and client could be resolved only by a struggle for power.

Now, it could be cogently argued that architects played a decisive role in reducing the (economic)

efficiency of building operations in the 1920s (Haber 1930, 71; *cf.* Woods 158). Nevertheless, the American architectural profession ultimately proved quite successful in promoting the divided-responsibility system through which it could most easily secure and maintain the power of its own members. That profession did so in part by promoting architectural-registration laws that had the effect of hampering design-build practice.[14] Holding that «a reputable architect must not engage in the business of construction contracting» (Banister 1954, 27) the American Institute of Architects meanwhile exerted strong social pressure on architects to avoid employment by contractors.

Much research remains to be done to reconstruct the history of construction management (as distinct from, though related to, building technology) in the United States. This contribution to such a history has shown that the growing interest in design-build evinced in the United States since the 1970s was not really a novelty. It is better seen as the revival of an approach to building procurement that had known considerable success in the first half of the twentieth century. In both periods it responded to pressures to increase the efficiency of building procurement. These pressures, perceived as imperatives, are practically identical to those still urgent today —decades after the divided-responsibility system achieved unquestioned dominance.

Notes

1. See advertisement appearing in the *Literary Digest* for 9 February 1918, 45.
2. See, *e.g.*, advertisements appearing in the *Literary Digest* for 30 March 1918 (55), 13 April 1918 (49), 11 May 1918 (34), and 6 July 1918 (60).
3. See illustrations in *The Hoggson Magazine* 1 (September 1914); 6, 34.
4. Information kindly supplied by Emily Troxell Jaycox from the records of the Missouri Historical Society. See also a Unit Structures, Inc., advertisement inserted into *Architectural Record* 130 (October 1961) following p. 48.
5. See advertisement appearing in *Church Property Administration* 12 (May-June 1948), 63.
6. See advertisement appearing in *Church Property Administration* 11 (September-October 1947), 48–49.
7. See advertisement in the *Los Angeles Times* 21 September 1924, pt. 5, p. 4, col. 4.
8. See the *Los Angeles Times* 19 November 1922, pt. 5, p. 14, col. 5; p. 16, col. 3; p. 2, col. 6 (advertisement).
9. *E.g.*, an advertisement appearing in the *Architectural Record* 104 (December 1948), p. 229, featured an apartment building attributed to the «E. L. Anderson Company, Chicago, Designers and Builders.»
10. See advertisements placed in the *Literary Digest* between 12 January and 5 October 1918, *passim*.
11. See advertisements in *House Beautiful* for March 1906 (p. 8) and January 1907 (p. 6).
12. This diagram calls to mind the slogan, «Steele Centralized Responsibility,» used slightly later by William Steele & Sons to epitomize its own practice as a design-build contractor (William Steele & Sons Co. 1919).
13. Information extracted from Los Angeles city directories, 1893–1906.
14. Two examples of litigation based on architectural registration laws, having the effect of restraining design-build operations, are: Meyer & Holler *v.* H. D. Bowman (121 *California Appellate Reports* 112) and Arkansas State Board of Architects v. Bank Building & Equipment Corp. of America (286 *South Western Reporter*, 2[nd] series, 323).

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The work and influence of Felix Samuely in Britain

David Yeomans

Development of structural forms as a means of architectural expression in Britain was encouraged firstly by engineers who worked for architects of the Modern Movement in the inter-war period and then by the need for innovative structural design to deal with the shortages in the period of post-war reconstruction. One of the key figures in this development was Felix Samuely who came to Britain in 1933 and was highly influential. This influence was partly because he was one of the more innovative engineers of this day and partly because his work was well reported in the architectural journals. In the inter-war period his work included a number of notable buildings including Simpson's Store, Piccadilly, London and the De la Warr Pavilion, Bexhill, whose forms let to the design of innovative steel frame structures. In the post war period of reconstruction his work was determined by the urgent needs of the country for factories and schools but constrained by the shortage of building materials. In this climate Samuely was to make considerable use of such devices as star beams, prestressed concrete and folded plates in both steel and concrete.

While the influence of other engineers on the architecture of the inter-war period has been chronicled Samuely's influence has received less attention. This study, based upon the archives of his firm considers the scope of his structural invention and the extent of its reporting in contemporary journals. It will provide a survey of his work to show the range of his structural designs and a commentary on the extent to which these were covered by the architectural end engineering journals to provide some measure of his potential influence on architects and other engineers of the time.

THE WORK AND INFLUENCE OF FELIX SAMUELY IN BRITAIN

The organization of design and construction in Britain involving the employment of consulting engineers does not result in the emergence of figures like Nervi or Perret. As contractors these men developed construction techniques that they used for a number of their projects so contributing o their overall architecture. It also means that their names have become associated with prominent buildings in a way that is unusual for engineers in Britain. In Britain the architect retains the lead role the variety of projects handled by consulting engineers means that rather than figures emerging because of their contribution to, or the development of a construction method, engineers have been successful through their ingenious use of available methods, their opportunity to use these dependent upon their ability to work with the architects who engaged them. This is the kind of contribution made by Felix Samuely whose work in Britain spanned the immediate pre-war and immediate post-war years.

Samuely left his practice in Germany and after first working briefly in Russia he came to Britain in 1933

where he decided to settle. In May of that year the Borough Council of Bexhill had given approval for the construction of an entertainment pavilion the design competition for which was won by his fellow émigré Eric Mendelsohn who then employed him as consulting engineer for the structure. Thus his career in Britain was immediately launched. The significance of this building was that it was both a major Modern Movement building in a country that had been rather slow to adopt these new continental ideas and the first major architectural project to use welded steel. Samuely then attracted a number of other clients from the Modern Movement in Britain much of this work involving the houses and apartments that they designed. His contribution to the architecture of the period is apparent just from a list of the architects and their projects that he was involved with. In construction terms t is for his contribution to the early development for welded steel in buildings that he is best remembered but he also showed some ingenuity in the pre-war use of reinforced concrete.

Immediately after the war, with his reputation established, he contributed to the schools building programme, a major undertaking in post-war Britain (Saint 1987). The scale of Felix Samuely's involvement in this may be gauged by the 37 schools and 6 college buildings that he was involved with in the years between 1945 and 1952. In the work on these he developed the use of precast concrete and folded plate construction, sometimes combining them, and showed considerable engineering flair in other ways, often needed at that time to overcome shortages of construction materials. His involvement with the Festival of Britain and the design for the Skylon, an engineering tour de force, was a far more visible manifestation of his talents, and there were other major projects in which he used prestressed concrete, another innovative form at the time. Nevertheless it is the less-visible engineering of his schools projects that is more important in the context of this conference. He was also keen to publicise the work that he did. This may have been with the intention of attracting more work but is more likely associated with his interest in teaching. In either case, its effect would also have been to bring the structures that he used to the attention of others and so help widen the use of these techniques.

WELDED STEEL

The development of steel structures in Britain had been hindered by the rather restrictive building regulations. In fact there were problems with the introduction of any novel form of construction because of the prescriptive form that these regulations took, enshrined either in the Model By–laws or in the London County Council (LCC) Building Acts. Regulations for steel construction had been produced for the latter in 1909, before welding for building had been contemplated and by the late 1920s the situation for bolted or riveted structures was also far from satisfactory. A Steel Structures Research Committee had been set up to look at the rather irrational methods of design being employed and a Welding Panel of this committee was formed in 1930 but, as was pointed out at the time (Caldwell 1930, 104–5), the development of welding as a practical method of building construction was still hindered by the LCC Act. Other local authorities, without the resources to develop their own regulations, tended to rely upon the London rules for both steel and reinforced concrete frames. Nevertheless it would be misleading to suggest that there were no welded steel frames put up at that time nor that there were not those who were experimenting with the use of welded construction in large scale buildings (see for example McBride 1935). It seems to have been easier to use this and other new forms of construction outside London where local building inspectors could be persuaded to relax the regulations.

Of course it was most often for factory structures that welded construction was used. The journal *Architecture and Building* (1932) had reported an all welded factory for The Matrix Welding in 1932 and the following year the Bata shoe company put up a factory in England, the technology for which was simply imported from its native Czechoslovakia (*Architecture and Building* 1933). Helsby, the engineer with whom Samuely went into partnership, had also designed welded steel structures and published articles on these (Helsby, 1932 & 1934) and it may well be this mutual interest that attracted Samuely to joining him. The significance of Samuely's contributions to this development was the prominence of the buildings that he worked on, the comprehensive use of welding within the structure and the novel forms of construction thus introduced.

De La War Pavilion and Simpson's Store

R. B. White (1966) claims that Mendelsohn and Chermayeff's original idea was to have a reinforced concrete structure with the intention of being able to have continuous soffits, unbroken by projecting beams but that steel was chosen when this proved impossible. The possibility is that they had gone to Kiers for the structure, which is where Samuely worked on first coming to Britain, and it was the opportunity to design a steel structure that was the stimulus for his going into partnership with Helsby and Hamman. Mendelsohn would surely have known Samuely as having worked on the first all-welded steel-framed building in Berlin. But the pavilion required a little more than a basic welded frame. There were a number of areas where some ingenuity was required to meet the requirements of the architecture. Of course, much of the ingenuity in the structural design was completely invisible and only apparent by looking at the structure in detail.

The central section of the plan in the area of the conference room was to be kept free of columns on the first floor and because of this the second floor was suspended from plate girders in the roof. The hangars for this comprised 1/2» plate, which could be housed within the thickness of the partitions and which went through the flanges of the plate girders and was welded to their webs. Hangars were also used in the external wall because of the continuous run of doors and windows on the ground floor. The lintols over these were suspended at intervals from the plate girders above. But the large areas of wall above these openings also presented problems for carrying wind loads back to the columns. The solution here was to use pairs of channel sections with plates welded between to form Vierendeel girders, another welded structure. All of this was hidden within the construction of the external wall.

Where the advantage of a welded structure was more apparent was in the handling of the staircase, which was an important feature of the architecture. Mendelsohn had made a feature of the staircase in his Schocken Department Store in Stuttgart where it had projected from the front of the building at the corner. At Bexhill he used a similar device at the centre of the building to divide the auditorium area from the restaurant but made this more dramatic by not only enclosing it within a glazed curtain wall but also by carrying cantilevered balconies round the outside of this curtain wall in a semicircle (Fig. 1). Only two columns were used to support the balconies and in order to carry the torsion moments their curved beams had to have a very heavy web section to limit their thickness while the columns were built up as strong box sections to carry the bending moments. Welding also helped with the long spans of the auditorium roof that had trusses at nearly 12 m (38′6″) cts with the shallow pitched roof trusses spanning nearly 23 m (74′10″). Secondary girders 1,5 m deep spanned between these. Shortly afterwards Samuely was also to use welded steel trusses for the roof of film studios at Shepperton (*Architects' Journal* 1936a).

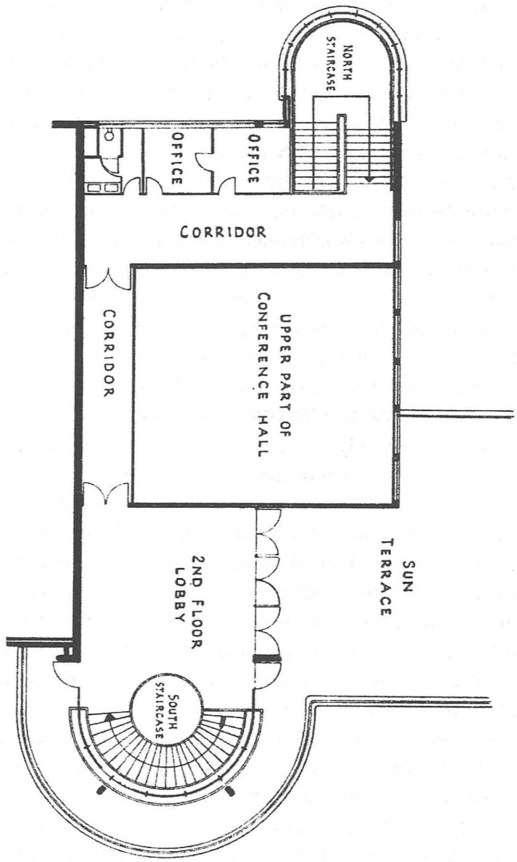

Figure 1
De la Warr Pavilion, Bexhill. Upper floor plan of the central section showing the way in which the sun terrace is carried round the outside of the main stair

Immediately following its construction Samuely published a series of articles in *The Welder* (Samuely 1935) but this series was not likely to be read by architects, and possibly not even by the majority of structural engineers. Therefore it was its coverage by the architectural journals that would have drawn the attention of architects to the possibilities of welding. The building was indeed well reported in these journals both for its architecture and its structural novelty. However it was Samuely's next major essay in welded steel that was to attract more attention for this aspect of its construction largely because part of the original structural design was not put into effect.

The publicity surrounding the design of Simpson's Store, in Piccadilly, London was significant partly because it so clearly demonstrated the restrictive effect of the LCC building controls. The original intention was for columns on the front elevation supporting upper floors to be brought down to a deep welded structure that spanned across the first and second floors but objections from the LCC required the loads to be carried by beams at each floor. That the resulting structure had a much greater weight of steelwork ad so was far less satisfactory was made clear in a detailed study by the *Architects Journal* (1936b) (Fig. 2). It is also clear from the drawings for this article, and from progress photographs, that the large welded structure had already been fabricated before the decision against it was finally made. The top and bottom chords of the first and second floor frame were simply placed in the building without the end pieces that would have connected them together and transferred the bending moments. Above this the plate girders to carry the other floors were conventionally riveted because the steel fabricators did not have the capacity to weld these; presumably they could not be produced in time. In spite of the difficulties with the frame at the front of the building welded steel was used elsewhere in the construction and many of the welding details, including those of the staircase were illustrated by the *Architects Journal* (Fig. 3).

By this time the situation for welding appeared to be improving as the LCC regulations were changed in 1935 following which Helsby and Samuely (1935) published an article that discussed these regulations in some detail. Samuely also designed other buildings using welded steel including Whittinghame College, Brighton that was partly welded steel and partly

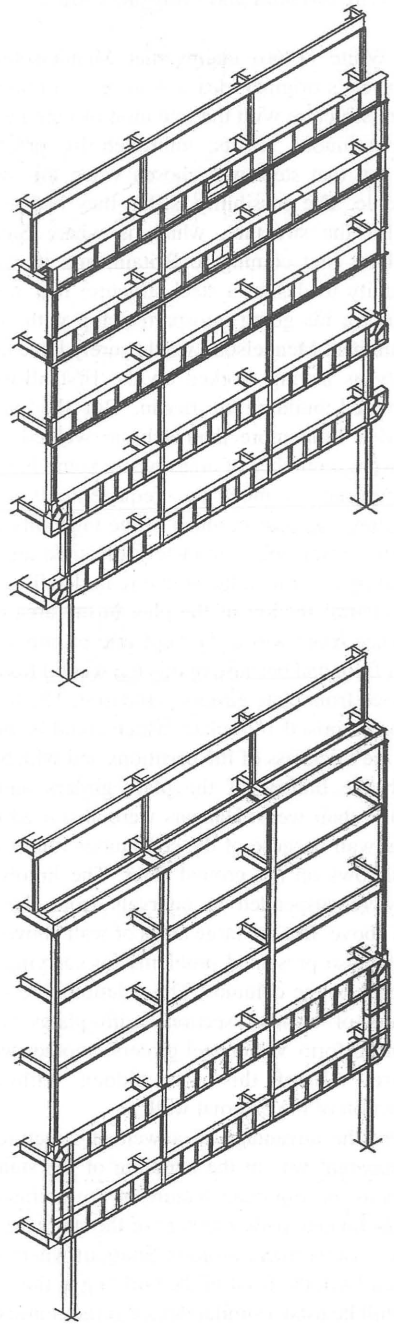

Figure 2
Simpson's Store, Piccadilly, London. Analysis of the frame as designed and as built. From *Architects Journal*

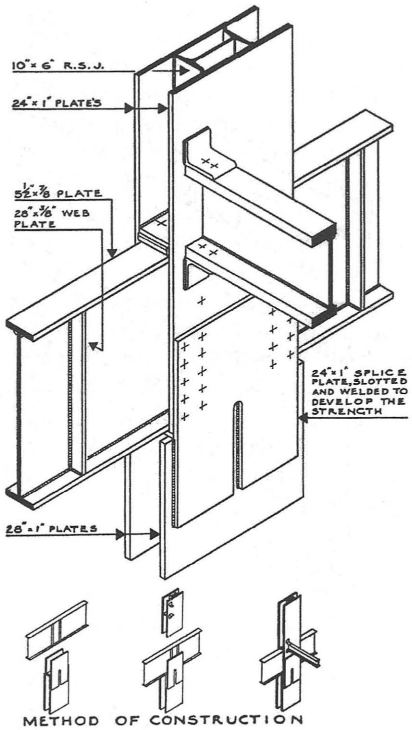

Figure 3
Simpson's Store, Piccadilly, London. Details of the welded frame. From *Architects Journal*

reinforced concrete, and described in considerable detail in the *Architects Journal* (1936c). Although largely a reinforced concrete frame building (see below) part of it had a steel frame with stanchions formed of angles welded together. The roof trusses over the assembly hall had T section chords with 1″ diameter rod bent to form the internal members —a precursor to the light trusses that were developed as standard building products and used extensively after the war. (Fig. 4) Whittinghame College also used a form of concrete construction that presaged a past-war system because Lewis dovetail sheeting was used as both permanent shutter and reinforcement for the concrete topping (Fig. 5).

Reinforced concrete

Samuely's possible contribution to the development of reinforced concrete design is less clear. In his first few months in Britain he worked with Ove Arup at Kiers and both were to use a form of structure that broke from what was the norm until then. Reinforced concrete had been used almost as a substitute for steel —simply as a series of repeated frames on a regular grid. The only alternative had been the use of flat-slab construction, introduced into Britain through links

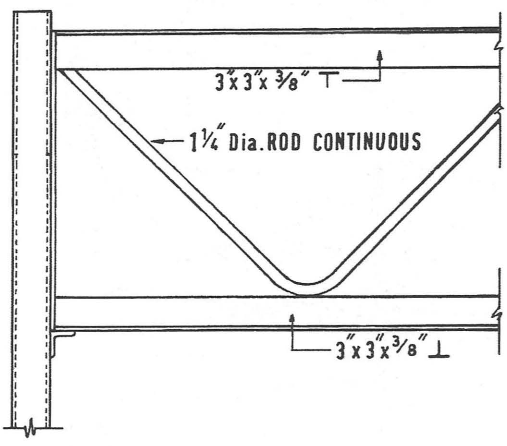

Figure 4
Whittinghame College, Brighton. Detail of the welded roof truss over the hall

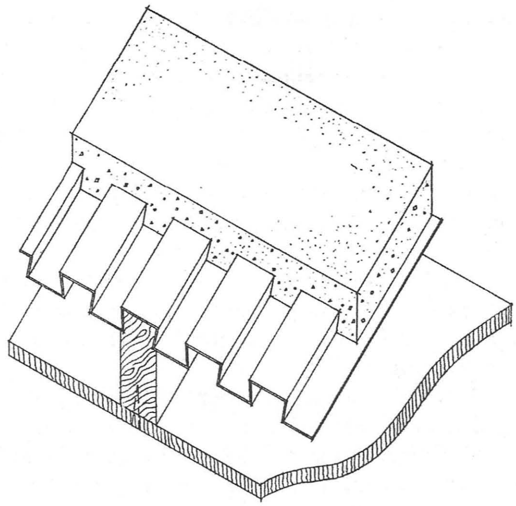

Figure 5
Whittinghame College, Brighton. Detail of concrete roof construction.

with the United States, another form of construction that had run foul of the LCC regulations (Yeomans. 1997). The way in which both Arup and Samuely used reinforced concrete was to treat the external wall frames as primary structural elements with the floor slab spanning across the building to a spine beam (rather like medieval timber-frame construction). Apart from eliminating the regular frames of columns and beams across the building, this arrangement allowed greater flexibility in the placing of columns because there was no necessity for those supporting the spine beam to respond to those on the external walls, nor even for them to be equal distances apart; they could be wherever was convenient for the plan. Arup used this arrangement in his Highpoint One design for Tecton and for their winning entry for the Cement Marketing Company's Working Class Flats competition (Yeomans and Cottam 1997).

Samuely used this structural layout for Gilbey's offices in Camden Town, London. These offices were sealed against the street noise and so required air handling ducts and these ducts were incorporated into the structural spine of the building. He used it for the concrete framed part of Whittinghame College for Pilichowski (Fig. 6) (already referred to above). (He also used this structural layout for a house in Chelsea for Mendelsohn and Chermayeff (Myerscough-Walker 1937; Yorke 1937, 32–33) although the latter was a brick building with the spine beam of steel.) But most noticeable at the time was its used for a small block of flats in Golders Green by Pilichowski, whose structure was described in some detail by *Architectural Review* (1935), likening it to the skeleton of a fish. No engineer was credited with this design but as the construction was by Kiers (*Builder*, 1936) one might assume that the design was by Arup. However, that Pilichowski subsequently chose to go to Samuely for the structure of Whittinghame College suggests that his flats might also have been designed by Samuely in the period during which he worked for Kiers. Given Samuely's subsequent track record in getting his buildings described in the journals it would not be surprising if he were to prove to be the author of both building and structural explanation.

Samuely's real demonstration of the possibilities of reinforced concrete for new structural forms came with his collaboration with Wells Coates for the Palace Gate Flats, London. He had already worked with this architect for some flats in Hove but these were fairly conventional in their structure. The Palace Gate flats were far from conventional in either plan or structure. Coates had been experimenting with three-dimensional planning in his own studio apartment and was now to apply a similar idea on a much larger scale to a complete block of flats. The three-dimensional way in which the accommodation was arranged would simply not have been possible with a conventional structural frame. To accommodate the complex planning Samuely had to design walls to act as beams and to hide other beams within the depth of the floor slab. This was another well-publicised building with an extensive coverage in *Architectural Review* (1939). But although it was a clear demonstration of the kind of freedom in planning that was possible to architects through the imaginative use of reinforced concrete it could not have had any

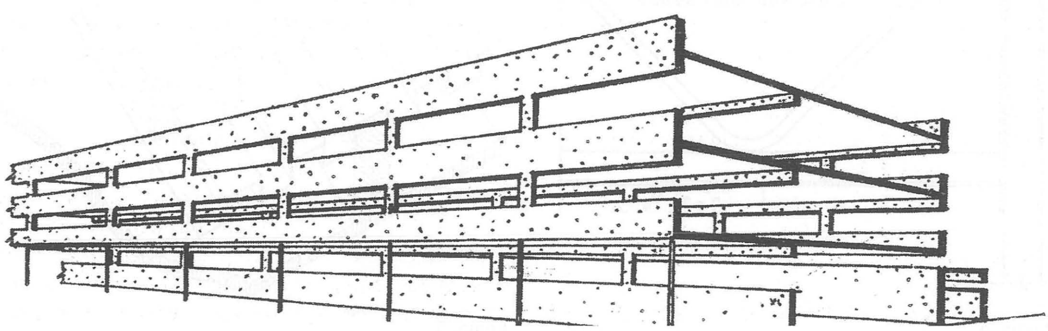

Figure 6
Whittinghame College, Brighton. General layout of the reinforced concrete structure

immediate influence on the architects of that generation because of the onset of the Second World War

Post war reconstruction

In the post-war period Britain required a massive building programme, partly to make up for the destruction caused by the war but partly because of there had been no building during the war other than for war purposes. Schools and housing were now the principal and urgent requirements. The difficulty facing the country was that the need for these buildings came at a time when there was a severe shortage of building materials and a massive foreign debt. Timber was a particular problem because Russian supplies were no longer available and Britain did not have sufficient foreign exchange to buy from North America. But there was also a shortage of steel that encouraged the use of reinforced and prestressed concrete rather than steel-frame construction. In this climate engineers looked for structural solutions that would economise on the use of materials. Not only was there a tendency to produce rather «tight» designs but there was also an advantage in finding structural forms that would be more efficient and methods of construction that would economise on materials. While concrete was preferred because of the saving of steel, precast concrete was preferred to insitu-concrete because it could reduce the amount of formwork needed and prestressed concrete was preferred to simple reinforced concrete again because of the saving in steel. Moreover, in the immediate post war years it was not simply price considerations that affected the choice of scarce materials but the requirement for building licences that allowed the authorities to control those that were used. In this climate Samuely developed techniques that economised on the use of materials and that were to form part of the repertoire of techniques more widely used in the post-war years.

Precast concrete

Precast concrete had the advantage that it saved on the timber required for shuttering. An example of this was a laboratory for Fina Petroleum at Orsett for which precast concrete was reportedly used because the authorities would not release plywood for the shuttering necessary for in-situ concrete (*Architect and Building News* 1952). Both frames and floor structures could be precast, the engineering issue for the former being to make connections between the frames. Many of the structures that Samuely devised used precast concrete wall frames, as in the laboratory building referred to above although Hatfield College used dramatic two storey high transverse frames. As such this was reported in some detail in the *Architectural Review* (1953) while the less dramatic wall-frame structures received less attention. This and a number of Samuely's other structural innovations were used in Thomas Linacre School, Wigan that was widely reported in the journals (e.g. *Architecture and Building*, 1953: *Builder* 1954) although not well illustrated.

The main teaching blocks used precast concrete frames to form the external walls with the floors spanning 6,9 m across the building between them. These precast frames here were fairly simple comprising pairs of columns at approximately 1m centres with head and sill members cantilevered half a bay beyond them. Bolts and steel plate connectors were used for the precast units so that as much as possible of the construction was dry. This was to save formwork and such a composite of precast and insitu concrete was to become part of the firm's stock in trade. It was reported that the floors were cast as erection of the frame proceeded from one end to the other.

The journals that reported this building did not include drawings of the construction and for this we have to look at other buildings of the time. A larger scale version of this wall-frame arrangement that was to become an important type of construction was later used on a larger scale by Samuely for Fielden House, an office block in London that was described in detail by *Architecture and Building* (1954a & b). By now the idea had been developed with short sill and lintol pieces to connect adjacent frames and with the floor structure formed with secondary beams and Samuely's system of precast troughs to form a permanent shuttering composite with the insitu topping above (Fig. 7). The illustration shows another Samuely device that he used widely. His floor structures often comprised a series of thin precast concrete troughs over which there was an in-situ

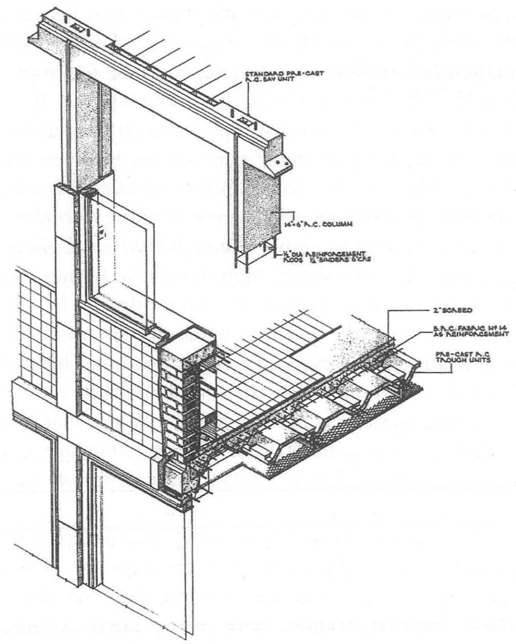

Figure 7
Fielden House, London. Precast concrete wall frame and composite precast and in-situ concrete floors.

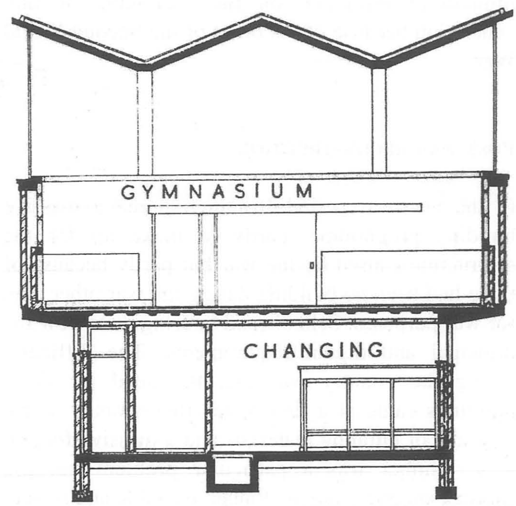

Figure 8
Woodberry Down School, London. Section through the gymnasium showing the folded plate roof

topping to produce a composite precast and insitu structure.

Folded plates

One of the effects of the post war shortages seems to have been to encourage the development of shell roofs for factory building. Before the war Samuely had designed a shell roof for Folkestone Rotunda and published the calculation method used for this (Samuely 1938). However, the advantage with folded plates was that the flat elements of which they were composed could be precast so that little insitu formwork was required. In schools, assembly halls and gymnasia had large spans that provided the opportunity for the use of folded plates. The most dramatic of these was for the gymnasia buildings for Woodberry Down School, London where the folded plates are arranged like bird's wings to provide clerestory lighting. (Fig. 8) But this was unusual and we might suppose used for architectural effects as much as for economy. His other roofs are far more conventional. At Thomas Linacre School he constructed the roof of the hall using a folded plate formed of precast concrete elements with an insitu topping.

The overall form comprised four planes of concrete that here spanned 14.5 m across the hall and nearly 23 m between end supports but with an additional 4.6 m cantilever at he stage end. One advantage claimed for this form was that the windows could be carried to the soffit of the roof. But this architectural advantage seems nothing to the constructional advantage of the method. Instead of requiring formwork to support the concrete each plane of the roof was first formed of precast concrete trough elements 2,5 cm thick but about 10 cm in overall depth. These could simply be supported on three lines of scaffolding down the length of the hall while insitu concrete was cast over them. Although (as noted above) this building was reported in a number of journals none provided any technical details of the construction and for this we have to look at Kingsmead School, London that was of smaller span

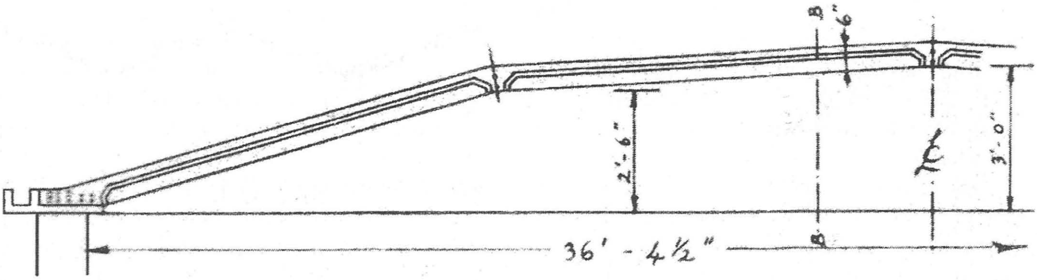

Figure 9
Kingsmead School, London. Details of the folded plate roof over the hall

but formed in the same way (Fig. 9). The *Architects Journal* (1953) reported on the construction of this school noting that the insitu concrete was a 5 cm screed with transverse top steel to take local bending moments. It also noted that the main steel «has been bent up in the plane of the roof along the lines of principal stresses» and that «ridges were cambered to counteract the expected deflections.» In the event the deflections were less than expected. Although it would be foolish to claim that it was entirely the result of an economic roof structure Kingsmead School was particularly cheap. The Ministry of Education imposed a limit of £170/place on the costs of schools in its building programme; the article noted that Kingsmead was built for £154/place.

Prestressed steel

Of course folded plates could equally well be constructed of steel and Samuely produced a number of these. The roof of the workshops at Thomas Linacre school had what was reportedly the first example of prestressed steel in Britain (Prefabrication 1956). Samuely had been involved in an essay in prestressed steel two years before when he designed what was presumably intended to be a standard roof design for Sommerfelds, a firm of steel fabricators (Architects Journal 1954). This roof consisted of pyramids of sheet metal carried within frames made of angles but with tubes between their apexes to form the top chord. This was prestressed with cables within the steel tubes and was to be erected on the ground and lifted into position. But although a prototype was built it may not even have been marketed.

The workshop of the school was quite different except that it too was assembled on the ground and craned into position. From the outside all that one sees is a pair of simple hip-ended roofs, the plan of which is seen in figure 10. However they are essentially folded plate structures spanning in the long direction and thus providing an interior space without columns. Sections of each slope were first welded up and then assembled to form a complete roof section that was lifted into place. The prestressing cables within this that take the form of a bending moment diagram in the slope of the roof

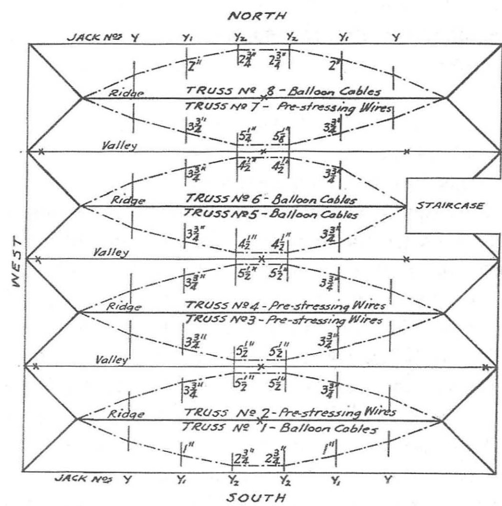

Figure 10
Thomas Linacre School, Wigan. Plan of prestressed steel roof over the workshops

were then fixed into position. Figure 10 is taken form a drawing made at the time to record the prestressing process and the amount of lift generated as it was applied. Lines marked «y» are the rafter positions, there being no diagonals within the roof. It shows that a combination of purpose-made prestressing cables and barrage balloon cables were used for the prestressing. At a time when there was a shortage of steel the now surplus balloon cables were used as prestressing cables in a number of building structures.

PUBLICATIONS

That Samuely's buildings were extensively reported in the journals of the time may be partly attributed to his work with Modern Movement architects. The journals naturally had an interest in this development and the significance of the structural engineering contribution. At the same time Samuely was interested in publishing himself, an interest that he seemed to share with Haman, one of his pre-war partners. A comprehensive study of Samuely's publications would occupy a paper in itself and only a brief summary is possible here. At first his publications considered technical issues of design and construction. As well as the series of articles on the structure of the Bexhill Pavilion he wrote another on the use of welding for Vierendeel s in roofs (Samuely 1937). But he was as interested in communicating with architects as with fellow engineers. Just before the war he produced a book on building construction in collaboration with his partner Hamann (Samuely and Hamann 1939a) and while a second volume was written the coming of the war prevented its publication: instead they produced a book on the design of air raid shelters (Samuely and Hamann 1939b). After the war he wrote for architectural publications, dealing in particular with space frames and stressed skin structures; structures that derived their properties from their geometrical forms (Samuely 1949, 1952a & b). This proselytising, if it can be called that, even extended across the Atlantic when he gave short on space frames (Samuely 1953) that was a keynote address in a discussion between a number of eminent architects and engineers that was reported in *Architectural Forum*. Samuely also provided the structure of a church in Connecticut for Wallace Harrison that used precast folded plates (for details see Wagner 1998).

The post-war period was one where architects had become aware of the architectural possibilities of modern structures and Samuely was interested in contributing to this development, publishing far more than would normally be expected of a consulting engineer. Meanwhile the buildings on which he worked continued to attract the attention of the architectural press. Elsewhere I have suggested that the need for economical designs in the immediate post-war shortages was a contributing factor to the development of a climate in which consulting engineers were rather more routinely engaged instead of leaving the structural design to be carried out by the contractor's engineer (Yeomans 2000). However another factor was emergence of consulting engineers who were both able to take an active role in the design process and also to design structures that went beyond simple frames. Samuely was not only a leading figure among such engineers but was the most active in developing methods of construction that could be applied widely. This has only been a sample of the work that he did and the structural devices that he used. A full appraisal of his work has yet to be carried out.

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Large roofs, large spaces. Suspended cable roofing in Italy 1948–1970

Luigi Zordan
Renato Morganti

Proudhon, writing of the Halles Centrales markets in his *Du principe de l'art et de sa destination sociale* of 1865, said: «for a market where perishable products are stocked, the ideal would be to be situated in the open air. Since the uncertainties of our climate do not permit this, it would be better for the roof to be in some way *suspended* from a hook, high overhead, like a lamp from the ceiling; . . . the columns that hold everything up should occupy as little space as possible.»

Proudhon's remarks point to at least two circumstances. The first concerns the growing demand throughout the 19th century for buildings with large covered spaces, freed from bulky vertical supports to permit the new functions that had come to enrich the urban panorama to proceed unimpeded: from exposition halls to warehouses and covered markets, from railway stations to commercial arcades, from museums to libraries. The second is more specifically concerned with a method —and one which was certainly alternative to those in current use— for covering large spans: the technique of suspending roofing framework directly from straight ties or cable-stays. First used for bridges, this technique was then successfully extended to roofing, though the number of examples constructed up to the 1940s was fairly limited (Zordan, Morganti, 1996, 9–67).

In Italy, it was not until the second half of the '40s that the first suspended cable roofs appeared, first for temporary pavilions erected for national trade fairs, and later for buildings that were intended to be far more durable, as they were designed to house aircraft. Indeed, both the restrictions imposed by the Fascist regime's policies of economic self-sufficiency between 1935 and 1943 and a cultural climate which was anything but well-disposed towards attempts to push too far beyond the familiar ensured that this particular type of roofing was able to strike root in Italy only after the end of the Second World War.

The Milano trade fair in particular was one of the most active proving grounds for new departures in modern architecture, which was only rarely able to try its hand at such highly specialized enterprises. Almost all of the Rationalist architects then working in Lombardy made several appearances at this venue, where the pre-war group that included such names as Nizzoli, Albini and Carboni was joined from 1946 onwards by the young De Carlo, Gardella, Figini and Pollini, and Zavanella.

At the 1948 fair, one of the most noteworthy of the modern buildings was the Officine Meccaniche pavilion, designed by Renzo Zavanella following an earlier study carried out together with Bruno Negri and constructed by the contractors Feal of Milano. The pavilion provided a splendid setting for the futuristic «Belvedere» railcar, a brilliant new conception that set new standards for speed and comfort, and whose interiors were also designed by Zavanella.

Years later, in a letter of March 6, 1978, Zavanella wrote as follows to Roberto Zannotti, author together

with Marcello Cruciani of a monograph dedicated entirely to the railcar: «OM contacted me directly, appointing me to design and oversee the work involved in outfitting the railcar in question, as my work at the time had already earned me a certain reputation among the architects of the Rationalist avant-garde». As the Rationalist architect he saw himself as being, Zavanella thus designed the interiors of the railcar that was said at the time to practically fly above the rails. But his assignment also included designing the pavilion that would protect the railcar from the elements. For this pavilion, Zavanella opted for a type of roofing that was at once agile, lightweight and permeable to light, with a design centering entirely on the interplay between elements in tension: a design that conveys the idea of a rarefied mass entrusted entirely to a singular «poetics of the filiform» that takes its cue from Rationalism «explodes in the kind of plastic exuberance that finds a welcome stimulus to compositional freedom in the promotional nature of the advertising message.» (Irace, 1987, 64–73).

Six tubular lattice steel masts with removable connections of the same kind used for temporary scaffolding, positioned to one side of the longitudinal axis of the pavilion's rectangular footprint, angle upwards above the wooden decking, which is likewise inclined and interrupted by six circular holes through which the masts pass. Converging at the top of the masts are the thin cable-stays —two main suspension cables and one backstay— whose unsymmetrical fan arrangement further reinforces the intentional dissonances that mark the structure as a whole. An angled tie closes the main direct suspension system used for the roof. The spindle-shaped masts are connected to each other by a three-dimensional framed truss located on the outer side of the roof deck. The braces that assist in suspending the roof framing and in stabilizing the entire structure are secured to this truss.

At the 1950 Trade Fair, Zavanella topped his 1948 exploit with an even more daring and imaginative roof design, where indirect suspension replaces the direct suspension system. The expressive force of Zavanella's second design contrasts strongly with the wood and steel cable-stayed roof which the architect Scoccimarro —author together with Sironi of the cityscapes produced for Fiat at the 1936 and 1949 trade fairs— covered the open areas of the Turin automaker's pavilion, whose icily schematic approach prevails over any ineffective cravings for form.

Zavanella's architecture embodies a playful structuralism, entirely foreign to the technologically-minded «vernacular Esperanto» extolled in the 1946 *Manuale dell'Architetto* and to the culture that produced it (Tafuri, 1985, 18). In completed and highly original form, this is an architecture that expresses a degree of technological eminence that does not cut itself off from the subjectivity of the design act, and whose power would seem to spring from the desire to liberate itself from the geometric rigors of the new objectivity, undaunted by the unresolved issues that might be seen as a denial of one's cultural identity.

By its very nature, the context in which Zavanella was called upon to work —city of spectacle and wellspring of modern complexity— spurred the architect to marshal, with bold aplomb, the new signs of Italy's industrial society on the threshold of post-war reconstruction: in giving formal shape to his «tension machines», a personal re-reading of the Rationalist penchant for rigor, his creativity seems to

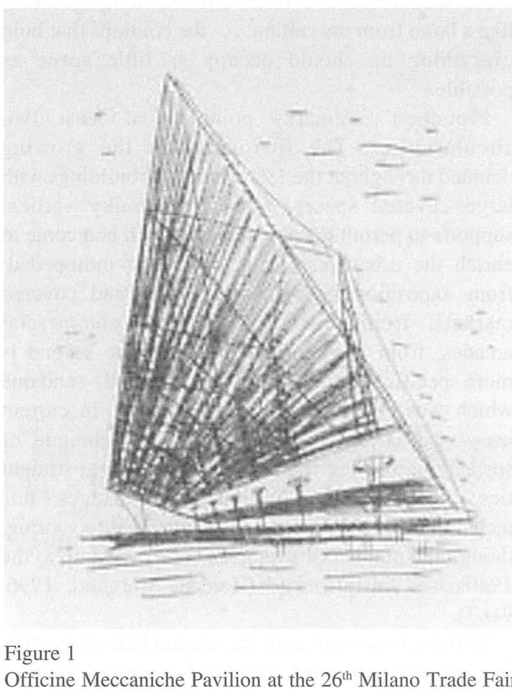

Figure 1
Officine Meccaniche Pavilion at the 26th Milano Trade Fair (R. Zavanella 1948): Sketch (Domus 229: 7)

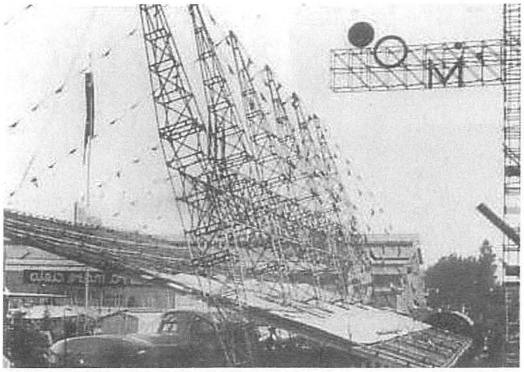

Figure 2
Officine Meccaniche Pavilion at the 26th Milano Trade Fair (R. Zavanella 1948): General view (historical archives of the Milano Trade Fair)

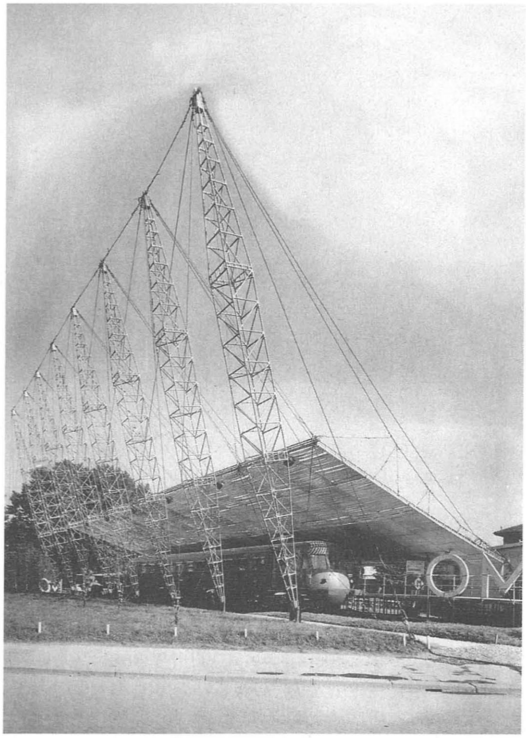

Figure 4
Officine Meccaniche Pavilion at the 28th Milano Trade Fair (R. Zavanella 1950): General view (historical archives of the Milano Trade Fair)

draw new strength from the work of the Russian Constructivists of the Twenties —Victor Vesnin and Anatole Ludwig paramount among them— and from that done in the Thirties by Le Courbusier who, though on a different scale, suggests using a cable-stayed roof for the stadium of a national sports and recreation center capable of accommodating up to 100,000 people.

In 1957, Officine Meccaniche participated in the 35th Milano Trade Fair with an open-sided pavilion constructed entirely of steel tubing which once again featured cable-stayed roofing. This time, however,

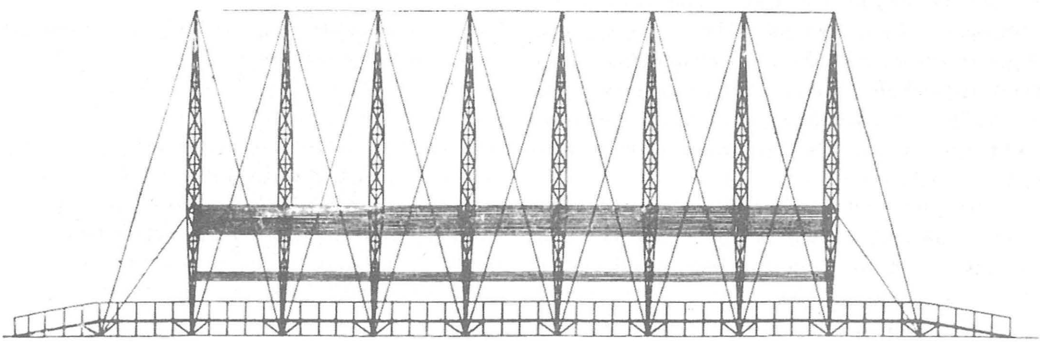

Figure 3
Officine Meccaniche Pavilion at the 28th Milano Trade Fair (R. Zavanella 1950): Elevation (l'architecture d'aujourd'hui: 48: 77)

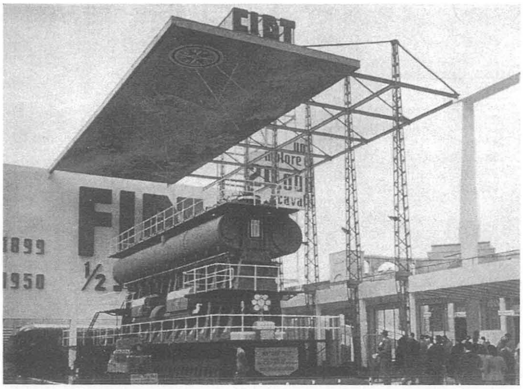

Figure 5
Fiat Pavilion at the 28th Milano Trade Fair (A. Scoccimarro 1950): General view (Costruzioni Metalliche 1950. 3: 6)

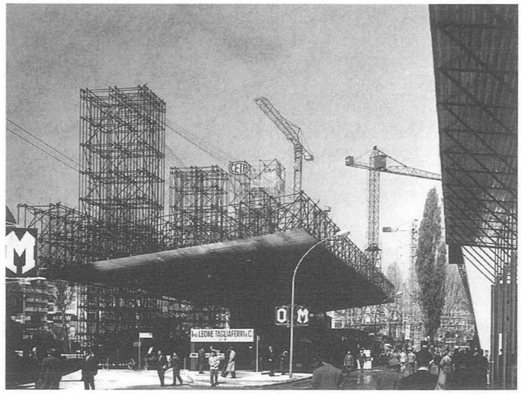

Figure 6
Officine Meccaniche Pavilion at the 35th Milano Trade Fair (unknown designer): General view (historical archives of the Milano Trade Fair)

there seems to be little room for the witty and imaginative exercises that distinguished Zavanella's work: here, we have an inextricable tangle of steel pipes for the piers and trusses, with a roof deck suspended from the slenderest of cables and whose structural members are all located on the exterior side. As a promotional statement, the pavilion still manages to hold its own, but its communicative power no longer springs from in the originality of the roof design, but from its sheer size and exuberance as a showplace.

Of the proposals advanced at the Trade Fair, city of spectacle and chosen stage for all that was most modern in Italian culture and architecture, few indeed were taken up by the real city. Thus, the suspended cable roofs of the early Fifties, including that by an unknown hand that protects the parking area and buildings of a gas station on the extreme outskirts of Milan, now look like alien fragments, meteors come crashing down from some other world.

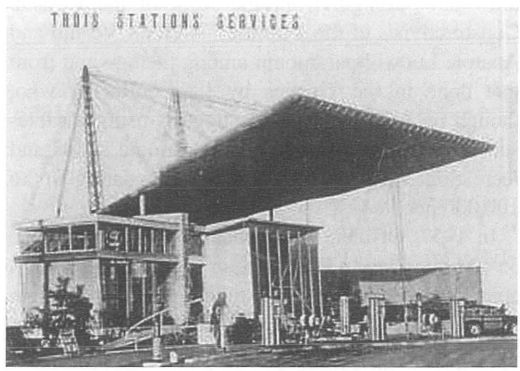

Figure 7
Gas station in Milano (unknown designer): General view (l'architecture d'aujourd'hui. 55: 74)

«On the international architectural scene of the late Fifties, the idea of the large structure took on a new and unaccustomed prominence. Experimentation in structural engineering, which, though by no means abandoned, had remained on the margins of architectural debate between the two wars, returned to center stage, thrust back into the limelight by the enormous growth of infrastructures . . . Underlying this widespread move to a new structuralism, we can see a renewed demand for internationality . . . In the international setting of the Fifties, in fact, while the overall backwardness of the construction industry is all too apparent . . . , and while architectural culture stands accused of «retreating from the modern movement», Italian structural engineering assumes a leading role.

That this should be so is one of the paradoxes that have dogged Italy in this century. And there can be little doubt that it is a paradox that can be explained, at least in part, by the massive investments that were

poured into infrastructures (the sector hardest hit by the war), and by the presence of designers of large structures of the caliber of Nervi, Morandi and Musmeci» (Poretti, 1997–1998, 96–102).

These are the contexts that gave rise to the first important uses of the directly suspended roofing technique in Italy, which not surprisingly took place between the end of the Fifties and the early years of the next decade. In our country as elsewhere, these applications were linked to the enormous growth of air transport.

With the construction of the Fiumicino international airport in Rome at the time of the 1960 Olympics, Italy's first aircraft hangers were built. This was an opportunity to propose the first suspended cable roofs capable of covering large spans without obstacles on the interior or at the aircraft entrance, and which could be extended if necessary along their major dimension. Umberto Venanzi and Gianfranco Vannacci, followed somewhat later by Riccardo Morandi, used this type of roofing in their designs, selecting the simple cantilever static layout that had been in common use in the United States for several decades as the most straightforward approach.

The first tender competition was announced by the Ministry of Public Works in 1958. The tender was awarded to Castelli Costruzioni Edili S. p. a. of Rome, who subcontracted design and fabrication to the Centro Carpenteria Tubolare Dalmine, where Venanzi and Vannacci worked as structural engineers. Once initial uncertainties concerning which type of solution was most appropriate had been overcome, a roofing design was chosen that made use of cable-stayed three-dimensional framed main trusses of various heights, all 52 meters long. Fabricated from tubular structural sections, the trusses rest on a steel lattice pier and are suspended from a rigid rod, whence forces are transferred to the ground via a mast and a bottom brace. Venanzi and Vannacci, however, did not go beyond a purely engineering approach to the project: once they had decided on steel, they were able to avoid wasting too much time on the details of the structural members, allowing the full constructional rationality of a building that was required to be both functional and economical to surface. The two Italian engineers' extremely pragmatic approach is in line with that which their American counterparts had been using for some years in dealing with the same constructional issues applied to similar types of buildings, employing highly sophisticated steel load-bearing systems and modifying them according to the size of the aircraft involved.

The second tender competition, announced in 1960, concerned a complex of hangers, storage facilities and office buildings for an Alitalia aircraft maintenance center to be located on a site adjacent to that occupied by the recently completed hanger. While Castelli submitted a bid for a design which was considerably less daring than that constructed two years earlier, the tender contract was awarded to Astaldi-Lodigiani-Salvi (A. Lo. Sa.), who had presented a design by the Roman engineer Riccardo Morandi.

Morandi approached the project in the belief that, as he wrote after the work was completed, « . . . the most modern advances in the art of building with reinforced or prestressed concrete are well able to rise to the challenges posed by the enormous mass of formal, technical and executive problems involved in this area» (Morandi, 1964, 695–710). In the final design, two symmetrically paired hangers surround the office buildings, and the central space is occupied by the maintenance shops. For the roofs of the two hangers, Morandi brings all of the design intuition he showed in his cable-stay bridges into play, showing a masterly balance between boldness and rigorous design control that is nowhere more evident than in the spatial arrangement and configuration of the structural members.

The challenge of covering spaces of over 12.000 square meters with no structural obstructions of any kind was brilliantly solved through the use of curving beams of prestressed reinforced concrete divided into three elements linked by articulations and suspended from stays consisting of bundled steel cables protected by concrete sheaths, which are also prestressed. As in the earlier American examples —which Morandi appears to have drawn on to some extent— the gap between the beams is spanned by ribbed reinforced concrete panels prefabricated on site in a workshop which also produced the beams and paired masts that were located on the firewall in order to transfer cable loads from the tops of the internal columns.

But Morandi's experience with suspended cable roofing did not end here. At the end of the Sixties, he worked with the same contractor in designing and

constructing Alitalia's Boeing 747 Maintenance Center, again at the Fiumicino-Leonardo da Vinci intercontinental airport. This time, the two hangers do not face each other to form a symmetrical organism, but are placed side by side: together, they form two large spaces, each around 6000 square meters, covered by a reinforced concrete cable-stayed tension structure with workshops and service buildings at the end. Morandi made the most of this new professional opportunity: rather than limiting himself to re-proposing the 1960 design, he takes wide-span reinforced roofing another and even bolder step forward. Technologically, Morandi's performance here was so exceptional as to take on all the semblance of an «austere monumental archaism» —fruit of a highly distilled reinterpretation of the «neo-Expressionist structuralism» that Morandi had espoused some years earlier with his design for the underground exhibition hall for the Torino Motor Show (1958–959)— emphasized by the imposing tapered columns that rise past the horizontal line of the thick beam crowning the structure. From the tops of these columns, the cable-stays extend in a radius pattern, upholding the roof deck consisting of reinforced concrete strips ending at two sturdy precompressed trusses and connected along their length by ribbed concrete sheets.

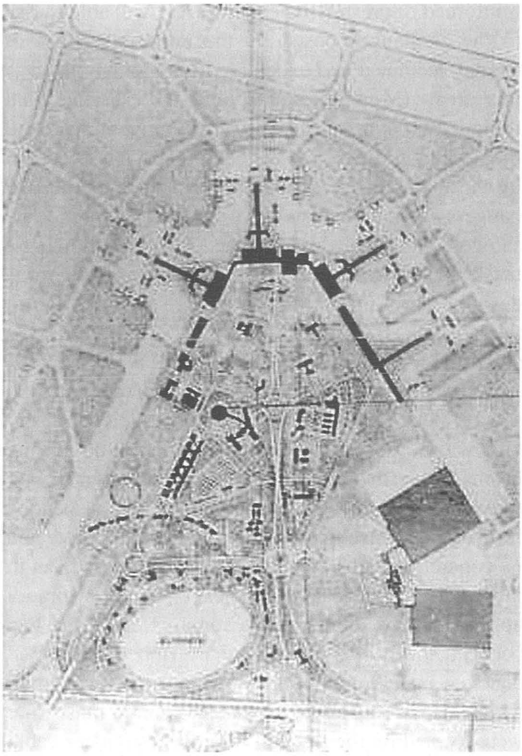

Figure 8
Fiumicino Intercontinental Airport, Rome: Plan view show showing the outlines of the new hangers to be constructed (Castelli costruzioni edili S.p. A. archives, Rome)

Another of the major achievements made in the field of suspended cable roofing during the Sixties carries the signature of Sergio Musmeci, a Roman engineer who received his training between 1948 and 1953 at the offices of Riccardo Morandi and Pier Luigi Nervi, from whom he absorbed the first rudiments of the structural designer's craft. By the years between 1963 and 1967, when he designed and built the Italtubi warehouse in Rome together with Livadiotti, Stegher and Cogliati, he had already collaborated with architects of the stature of Vaccaro, Libera, Vitellozzi, Quaroni, Zevi and De Carlo. Though he was the only prominent figure involved in the Italtubi project, the occasion was exceptional, not so much because of the building's importance, but because of the material selected and the type of roofing used. Abandoning concrete for the time being, Musmeci discovers the charms of steel and chooses the direct suspension technique for the roof. The building, now irremediably altered and virtually unrecognizable under a cladding of lightweight prefabricated panels, was essentially a simple canopy of corrugated fibercement sheets in a hexagonal layout using triangular grid elements, supported by three massive tapered compound-section central columns placed along the axis of longitudinal symmetry. Anchored to the top of the columns are the eighteen cables supporting the roof decking, which consist of formed and prestressed wire rope.

This was to be the only structure where Musmeci applied the direct suspension technique: the cable-stay bridges which he designed for Rwanda in 1978, in fact, were never built. It is nevertheless a building in which a highly personal view of the technological side of the Italian structuralism of the Fifties comes to terms, though perhaps in an over-simplified, mechanical spirit, with one of the motifs that organic architecture in Italy seemed almost duty-bound to follow in the same decade: the use of the triangular

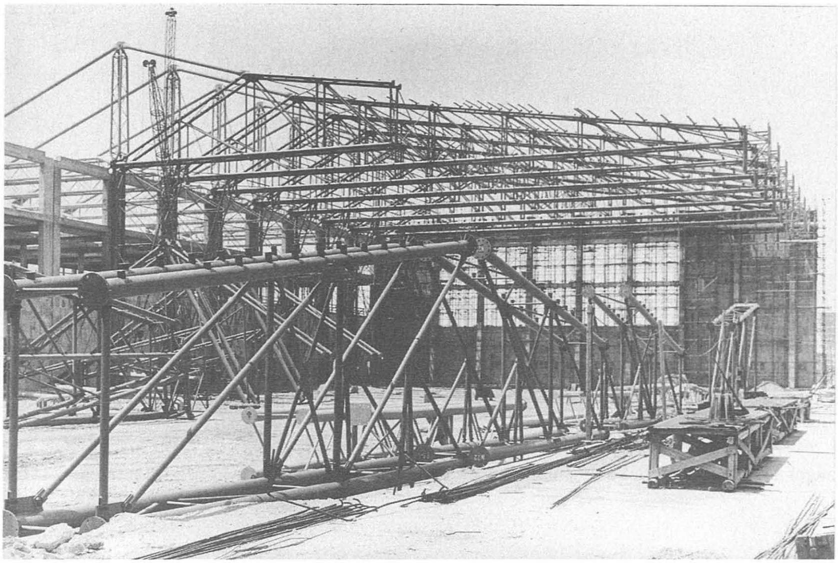

Figure 9
Hanger at Fiumicino Intercontinental Airport, Rome (U. Venanzi, G. Vannacci 1958–60): Installation of the three-dimensional framed roof trusses (Dalmine S.p.A. archives, Dalmine Bergamo)

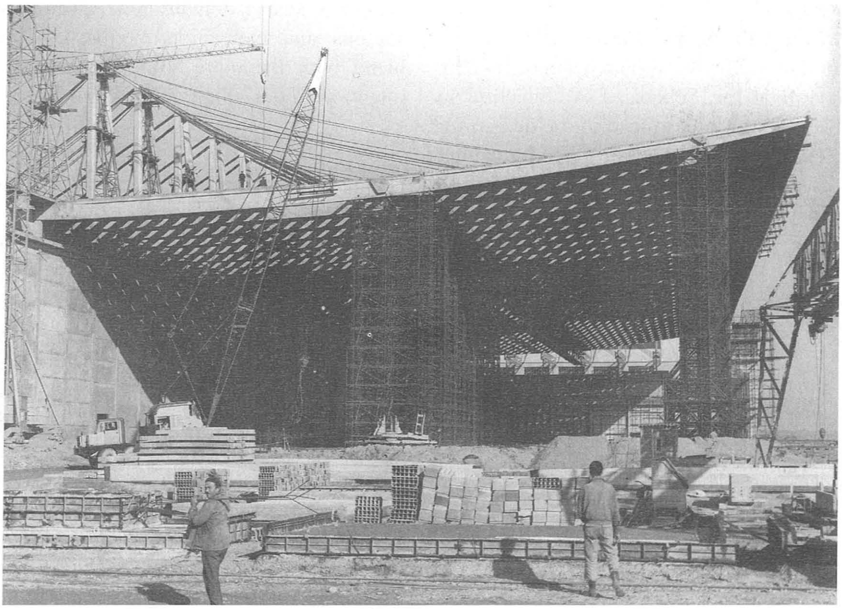

Figure 10
DC9 hanger at Fiumicino Intercontinental Airport, Rome (R. Morandi 1960–1962): Positioning the curving beams and rigging the cable-stays (Morandi archives, Rome)

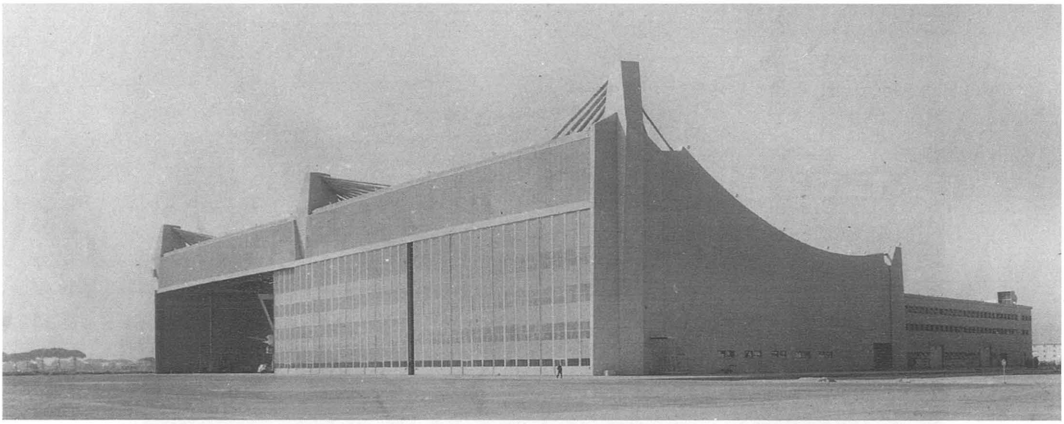

Figure 11
Boeing 747 hanger at Fiumicino Intercontinental Airport, Rome (R. Morandi 1969-1970): General view (Morandi archives, Rome)

grid as the basis of a structure's layout. There can be no doubt, however, that constructional functionality and static efficiency are here expressed in visible form, so much so that the building exemplifies what Musmeci himself called «structural architecture» (Nicoletti, 1999).

In the second half of the Sixties, we see the beginnings of the extensive research conducted by Leonardo Savioli at the School of Architecture in Florence. This research was to lead to the design for the new Pescia flower market developed together with Danilo Santi and others in 1970 at the time of a national competition sponsored by the municipal administration, though the market was not constructed until eleven years later. The cable-stayed roof of the main market hall derived from the architects' idea of using steel technology to evoke memories of past feats of engineering —the 19th century's suspension bridges, greenhouses, railway stations and exposition pavilions— which would blend with the more straightforwardly commercial intention of designing a building capable of standing

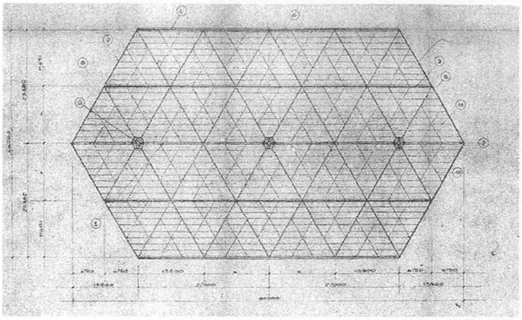

Figure 12
Italtubi warehouse, Rome (S. Musmeci 1963–1967): Plan view of the suspended cable roof (Musmeci archives, Rome)

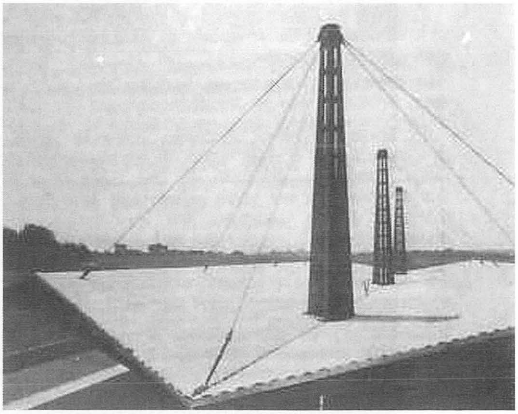

Figure 13
Italtubi warehouse, Rome (S. Musmeci 1963–1967): Suspended cable roof seen from above (Acciaio 1967. 12: 589)

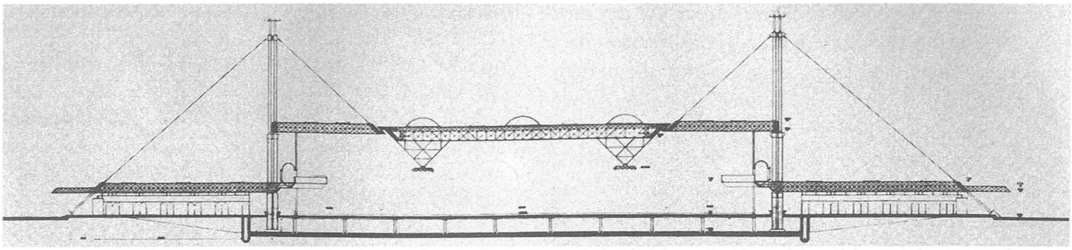

Figure 14
Pescia flower market (L. Savioli et al., 1970–1981): Cross sectional view submitted for the design competition (Parametro, 10: 85)

out from its surroundings and achieving landmark status. The careful attention devoted to the concepts of flexibility, adaptability and expandability resulted in a roof design featuring five independent portions, each part of a three-dimensional macro-module which is repeated to generate the main market hall. The primary structural system for carrying vertical loads consists of circular-section columns joined in groups of four and tapering upwards, while the flat roof deck, suspended from flexible steel cables with backstays anchored to the ground, is most noteworthy for its mixed configuration: the cladding, in fact, is supported by a space grid at the center and by one-directional framing at the sides. This is another aspect that makes the building —which represented years of painstaking work by Savioli and Santi, who were assisted by Cesare Pesenti and Luigi Nusiner in performing the calculations for the primary structural system— one of the most exceptional, in size as well as in design, ever erected in Italy. Elsewhere in Europe, its forerunners included the Soviet Union pavilion at the Brussels Exposition of 1958, which can be said to have contributed a number of construction concepts. For Savioli, the Pescia flower market was an important experience which, as part of an output dominated by exposed concrete, opened the door to further occasions for using steel, as it denoted a new way of looking at this construction material.

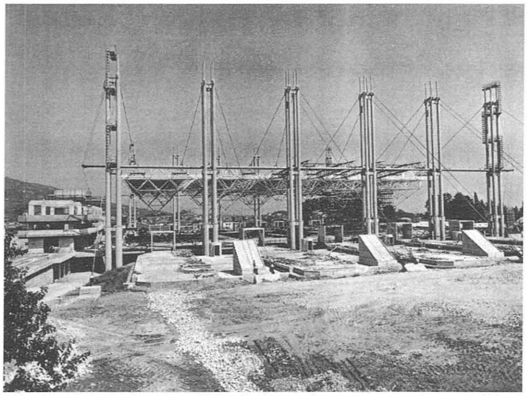

Figure 15
Pescia flower market (L. Savioli et al., 1970–1981): Final stages in the installation of the space grid (Dalmine S.p.A. archives, Dalmine Bergamo)

This work ended a decade and began another in which suspended cable roofing would once again find itself excluded from current design and construction practice in Italy, perhaps more than in other countries. From the standpoint of engineering calculations in particular, suspended cable roofing involved a series of unconventional problems that at first sight made it appear more complex than the issues engineers were ordinarily called upon to confront. On the design front, the calculation difficulties, which have now been largely overcome by increasingly sophisticated information technology, were joined by the problems involved in working out construction details and in planning building operations at the drawing board, which are closely linked to them. As regards operating practice, uncertainties remained concerning construction costs, not least because the lack of a well-established tradition in this area could easily lead to cost overruns.

Seemingly, suspended cable roofing is not destined to become part of the modern Italian construction site's repertoire. Nevertheless, and precisely because of their experimental and pioneering nature, the buildings we have illustrated exemplify a typical condition of modern architecture, freighted with unresolved problems, but also with an undeniable Utopian potential. Those who designed them —engineers or architects— though differing widely in background and culture, all worked in the full consciousness of devoting their professional energies to a sparsely populated field, and with the primary goal, not so much of setting unattainable records, but of finding their own voice amongst the clamor of avant-garde rationalism, technical pragmatism, organic structuralism or inspirational technology, as the case may be.

As for the future of this type of roofing, there is a widespread awareness that steel has surpassed reinforced concrete for wide-span roofs. In Italy, it will thus be the material of choice for all those who are called upon to deal with design issues of this kind in the coming decades (Zordan, 1996, 119–131).

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